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TRANSACTIONS OF THE TENTH SCIENTIFIC CONFERENCE OF THE INSTITUTE OF HISTORY OF NATURAL SCIENCE AND TECHNOLOGY

by Yu. V. Biryukov et al.

Institute of History of Natural Science and Technology, Academy of Sciences USSR, Moscow, 1967

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Translation of "Trudy X nauchnoy konferentsii aspirantov i mladshikh nauchnykh sotrudnikov instituta." Section of the History of Aviation and Cosmonautics, Institute of History of Natural Science and Technology, Academy of Sciences USSR, Moscow, 1967

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List of Abbreviations Used by the Translator

GSJP = Group for the Study of Jet Propulsion
LPRE = Liquid-propellant rocket engines
CGSJP = Central Group for the Study of Jet Propulsion
GDL = Gas Dynamics Laboratory
SRIJP = Scientific Research Institute of Jet Propulsion
ERE = Electric rocket engines
GTE = Gas turbine engines
TJE = Turbojet engines
TPE = Turbopropeller engines
BTJE = Bypass turbojet engines
TFE = Turbofan engines
TJED = A TJE with division of the air to the compressor
TJEAB = Turbojet engines with afterburners
TPA = Turbopump assembly

THE ROLE OF S.P. KOROLEV IN THE DEVELOPMENT OF SOVIET ROCKET TECHNOLOGY DURING THE PERIOD OF ITS ORIGIN AND ESTABLISHMENT (1930 - 1941)

Yu. V. Biryukov

ABSTRACT: The paper discusses the multiple roles of S.P. Korolev in the development of Soviet rocket technology during the period of its origin and establishment. Inspired by the teachings of Tsiolkovskiy and Tsander, Korolev went on to become instrumental in the organization of the Group for the Study of Jet Propulsion (studying liquid propellant rocket engines), and in founding the Scientific Research Institute of Jet Propulsion. He was an ardent propagandist of rocket technology; in his publications as well as in his own studies and directorships, he emphasized the importance of studying immediate practical goals, such as a manned rocket flight (realized on February 28, 1940, with the SK-9 glider, piloted by V.P. Fedorov).

Sergey Pavlovich Korolev entered rocket technology as an active participant at the very beginning of the thirties, and he became one of the world's pioneers in rocket engineering. /3*

The teachings of Tsiolkovskiy regarding the conquest of outer space showed the enormity of the perspectives facing mankind, aroused daring and talented people to the possibility of applying their energies to this challenging task, showed the basic feasibility of the idea, and gave hints as to the ways in which it could be carried out, but they did not answer the question of whether or not it was necessary and expedient to study the problem of making a flight into space at present, or whether this task should be left for the future.

Everyone who was then involved with the problems of astronautics was faced with this question, and everyone, depending on the level of his knowledge, his aspirations and his insight, gave some answer to this question. There were those scientists who "showed" that a flight into space was basically impossible, not even bothering to acquaint themselves well enough with the teachings of Tsiolkovskiy. Most of the scientists, as well as other people on whom the development of science and technology depended, considered that a space flight was not possible at the given level of development of the productive forces, and maintained that its realization depended

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* Numbers in the margin indicate pagination in original foreign text.

on the fulfillment of certain conditions (for example, on the mastery of atomic energy). If they recognized its feasibility, then they considered that working for its realization, which would require very great expense, was not timely or expedient.

However, there was another, fairly large group of people, mainly creative youths and unestablished scientists, who considered that a prompt beginning of studies of the conquest of outer space was necessary. Most of these people did not foresee all the actual complexities of the problem and so, having hardly matured and experienced their initial difficulties, they abandoned the entire matter. Thus, the Society for the Study of Interplanetary Communications broke up in 1924, the Interplanetary Section of Designers-Inventors, in 1927, and other space circles and groups followed suit. /4

When S.P. Korolev started in rocket technology, only isolated groups were continuing serious studies on the problems of astronautics, but they did not deepen or expand theoretical astronautics in any way, did not solve any complex problems on the mechanics of space flight, and did not look with hard logic for any new arguments on which the necessity and basic feasibility of space flights could be based. None of this could move the problem from a standstill, or serve as a basis for the beginning of serious practical studies in designing rockets, or (in relation to this) could play a significant role on the order of what had alreacy been done by Tsiolkovskiy.

Nevertheless, rocket technology developed rapidly around the end of the twenties and the beginning of the thirties. The determinant cause of this development was found, not in the works of astronautical theoreticians, but in the practical necessities of life, the requirements of such outgrowths of technology as aviation and artillery. At that time, many people already understood the great perspectives to be found in the application of the propulsion principle of motion in artillery and aviation, but it was still very difficult for them to apply these possibilities to actual life. N.A. Tïkhomirov and V.A. Artem'yev, in Leningrad, succeeded in doing this, because they decided to solve a narrow and completely real practical task. F.A. Tsander, in Moscow, was unsuccessful because he necessarily connected all his assumptions, even those for solving concrete and very close problems of rocket technology, with the problem of interplanetary flight. The result was an endless circle. In order to realise the idea of a rocket flight, it was necessary that it have public recognition, giving it the necessary means to carry it out. But the best way, and practically the only way at that time to obtain public recognition of the idea of rocket propulsion, was to accomplish an actual rocket flight.

The decisive role of S.P. Korolev first made a break in this endless circle. Having met Tsander, and having seen how much Tsander's dreams and goals coincided with his own and how much Tsander, who had already studied the problems of astronautics for

for more than twenty years, surpassed him in relation to his knowledge and experience in this area, Korolev first directed his energies to bringing Tsander's projects to life. In Tsander's OR-2 engine design, he provided the missing link for carrying out the idea of rocket aircraft, and a real basis for a broad development of practical studies on accomplishing rocket flights. He suggested that the simplest type of aircraft be constructed with this engine in the usual manner, with the aid of the Osoaviakhim (the Society for Assistance to the Defense, Aviation, and Chemical Industry of the USSR), under the same conditions as those under which many young designers, including Korolev, then produced gliders and light aircraft of their own design. /5

This idea, approved by the Central Committee of Osoaviakhim, was the basis on which, on August 18, 1931, the Group for the Study of Jet Propulsion (GSJP) was formally organized. The GSJP was the first group in our country which studied the practical possibilities for producing piloted apparatus with liquid-propellant rocket engines (LPRE). This apparatus was called the rocket aircraft "of the XIVth October Anniversary". F.A. Tsander was named scientific director of the group (with whom the Osoaviakhim later made a personal agreement for the construction of rocket aircraft [1]), I.P. Fortikov was named secretary, and the head of the studies on rocket aircraft was S.P. Korolev.

The new tail-less apparatus of B.I. Cheranovskiy ("BICh-II"), which was designed according to the same plan as the "BICh-8" (which Korolev had flown shortly before [2]), was used as the foundation of the rocket aircraft. The "BICh-II" aircraft was transferred to the GSJP in February, 1932, but the engine could not be produced in such a short period. The group did not have either the means or the qualified workers, and what had appeared to be an easy task of designing the LPRE and its devices for a glider turned into an entire complex of very complicated scientific research problems during the process of working on it. It was necessary to add new staff members, including those who were not simply interested in the problem of interplanetary flights, but who could be of aid in the practical development of rocket technology.

Thus, in practice, the members of the GSJP found the necessity of increasing the growth of technological forces, of increasing special knowledge, and of changing the nature of the propaganda: if the idea of space flights, their basic feasibility and great significance, had been the principal propaganda before, it was necessary at that time to show the significance of scientific and technological knowledge in the practical production of rocket technology and its importance for the modern life of the Soviet people. /6 They also encountered the necessity of preparing the proper types of specialists in rocket technology. Korolev had had experience as a propagandist of practical aviation-technological knowledge during his primary-school training, and he therefore began to play the leading role in the GSJP in this matter. He soon understood that aviation, as well as rocket technology, to a great de-

gree require the efforts of large collectives of people with different specialities, and he was therefore always very careful in attracting, preparing, and selecting the personnel. As a result, the first courses in the world on jet propulsion were organized with the GSJP, and the general nature of the propaganda changed. Korolev clearly described the purposes of the propaganda in a letter to Ya. I. Perel'man on July 31, 1932:

"Despite the great stress in the course of different experimental studies, we are all very preoccupied with the development of our massive work. Of course, it would be completely false to blame the problems only on the modern military, security-restricted aspects. In relation to this, a good example is the development of our experimental water-cooled graphite reactor. Only 1.5-2 years have passed, and the matter has expanded as widely and as broadly as our public opinion has become complicated. Therefore, we cannot doze off; we must assume and direct all the great initiative of the people so that a definitely positive public opinion can be produced regarding the problem of jet-propulsion, stratospheric flight, and future interplanetary travel. Naturally, we need literature during the first years. But there is no literature, except for two or three small books, and they are not available everywhere.

We think that it would be very timely to publish an entire series (10-15 volumes) of small popular books on jet propulsion, and then to discuss one problem in each book; for example, "What is Jet Propulsion?", "Fuel for Rocket Engines", "Using Rocket Engines", etc. These popular (and, at the same time, technological) books could be replaced in the future by a series of more specialized publications.

In general, we have written too much on all sorts of complicated and uncomplicated matters, calculations of how an interplanetary craft will land on the Moon and what will happen to it along the way, etc., while for the GSJP-circle, which is thirsting for knowledge, there are absolutely no materials..." [3].

Trying to provide such materials, Korolev paid special attention to work in the propaganda division of the CGSJP[1]; he delivered a number of lectures and articles, presented to the Central Committee of the Osoaviakhim the problem of publishing a journal, "Soviet Rockets" (adding, in this instance, a positive solution to the question of a journal [4]), and finally wrote the book "A Rocket Flight in the Stratosphere" [5]. This book, despite its popular-science title, was one of the only studies on rocket technology at that time. "The book is intelligent, inclusive, and useful", K.E. Tsiolkovskiy wrote [6]. /7

[1]The GSJP in Moscow was called the Central GSJP when similar groups arose in different cities. Afterward, it was often called the MosGSJP, while its design-construction and industrial base was simply called the GSJP.

Giving great significance to a massive study, Korolev also paid much attention to the individual selection of the personnel. As a result, the GSJP gradually became a solid, efficient collective, consisting mainly of specialists: engineers, designers and mechanics who had been in the aviation industry, many of whom had been connected with Korolev by joint studies for a long time. This gave a strong aviation technological flavor to the GSJP, and, through it, to all Soviet rocket technology. It is easy to see its significance by comparing (for example) the rockets designed by the GSJP with the rockets of the same type and title which were designed at the same time by the Gas Dynamics Laboratory, where the artillery school of design predominated. The rockets of the Gas Dynamics Laboratory were inferior to the GSJP's rockets in their weight and ballistic design characteristics, not to mention the fact that they could not be made to fly.

From the very beginning, the members of the GSJP had a high opinion of Korolev's contribution to their task. Thus, the secretary of the GSJP wrote the following to Tsiolkovskiy: "...Our experimental studies on the jet-propulsion rocket-aircraft "GSJP-RP1" are approaching an end... We have many highly qualified engineers, but the best of the best is the president of our Technological Council, the Engineer S.P. Korolev...He has already done very much for all of us. He will be the first to pilot the rocket aircraft..." [7].

The emphasis on propaganda regarding the immediate practical goals of rocket technology, solving real scientific problems in aviation and artillery by its aid, rapidly brought the GSJP recognition. The GSJP also achieved all the more recognition because it had a very weighty argument in the form of an almost ready (as it seemed then) rocket aircraft. The members of the GSJP also received aid from the vice-president of the Revvoyensovet, M.N. Tukhachevskiy. The directorate of military inventions gave them substantial means for their work. As a result, the Central Committee of the Osoaviakhim decided to organize a production base with the GSJP, called the "Experimental Plant of the GSJP", with S.P. Korolev as head and director of the entire CGSJP. /8

But it was still necessary to realize this decision. Whoever became involved in the "Experimental Plant of the GSJP" depended entirely on the members of the GSJP, and primarily on Korolev. He literally had to fight for everything - the building, the materials, the equipment, every tool. And this was not easy. The building, for example, was found and obtained from the Osoaviakhim and could be occupied only in the summer of 1932. It was even worse with the equipment. Many working drawings were ready, but there was nothing to make the parts with.

But the members of the GSJP overcame all the difficulties and produced a large (for that time) scientific center with substantial drafting, designing, research, and production possibilities. The

organizing talent of S.P. Korolev played the determinant part in all this.

Speaking of the emphasis on the propaganda and production work of the GSJP in connection with the immediate practical problems of rocket technology, we should pose this question: how did Korolev actually relate to the problem of interplanetary flight? An examination of the official documents and his published articles shows that during those years, he not only did not directly support studies on interplanetary communications, but he also dissociated himself from them to some extent. Thus, he wrote in his book in 1934 that "a rocket, due to its exceptional qualities, i.e., velocity and high ceiling, or the great range of its flight, is a very serious weapon. And this must be considered particularly by everyone interested in this area, and not in the still-unfounded fantasies on flights to the Moon and speed records of non-existent rocket aircraft" [5, p.10].

It would seem that this sharply contradicts the image of the extreme enthusiast and advocate of astronautics that characterizes Korolev in history. Actually, it only shows the complexity of the conditions under which the pioneers of astronautics began their work. Knowing that discussions of space flight at that stage compromised rocket technology in the eyes of many people who did not have too much insight into that relationship, Korolev preferred /9
not to mention astronautics and to do everything possible for its development, since much was said about interplanetary flights, and nothing approached them at all. Korolev showed his relationship to this question very precisely in another letter to Perel'man, on April 18, 1935, when he wrote: "I only wish that in your future works (since you are a specialist in rocketry and an author of a number of excellent books) you would pay more attention not to interplanetary problems, but to the rocket engine itself, to a stratospheric rocket, etc., since all this is now closer to us, more understandable, and more necessary. A great deal of nonsense has been written on interplanetary themes, and it is now hurting us badly.

Just a few days ago, they said directly to me in one journal: 'We are avoiding publishing materials on rocketry, because they are all lunar fantasies, etc.' Now I have even more difficulty in convincing people that this is not so, that rockets are a defense and science.

I would also like very much to see your excellent books in a series of studies to stir up enthusiasm for rocketry, flight and struggle for its prosperity. If this happens, then there will be a time when the first terrestrial craft leaves the Earth. Let us not wait for this; let them think that we are digging deep. All the same, successes are possible only on these grounds." [8].

Even while admitting such a possibility, Sergey Pavlovich, at

the same time a sincere supporter of the cause, did everything he could in order to bring this time closer. This is also indicated by the recollections of members of the GSJP, who say that Sergey Pavlovich was no less attracted to the idea of an interplanetary flight than was F.A. Tsander, and that he dreamed particularly of a flight to the Moon. This is particularly clear in the themes of the articles outlined by the GSJP, which pursued three goals: the immediate goal was to demonstrate, in practice, the reality of accomplishing a propelled flight and the expediency of doing it at that time; the principal goal was to conduct broad studies which would ultimately guarantee the most correct selection of the optimum path to the final goal, and which would give a great practical yeild in the form of new types of weapons and aircraft; the long-term goal was to investigate in particular detail those problems of rocket technology in relation to which it was already clear that space flights could not be realized without their solution.

These were the problems: to use liquid oxygen as the most promising rocket oxidizer, to study the problems of a manned flight on a rocket apparatus (both from the technological and from the medical and biological point of view, with the participation of a group of aviation doctors headed by Doctor N.M. Dobrotvorskiy), and, finally, to investigate the problems of using metallic fuel and designing an air-breathing jet engine for operation in the atmosphere. As we see, these subjects differed greatly from those of the Gas Dynamics Laboratory, which were intended primarily for production of rocketry weapons. /10

As a result of the purposeful activity of the head of the GSJP, S.P. Korolev, of the directors of the teams, F.A. Tsander, M.K. Tikhonravov, and Yu. A. Pobedonostsev, and of the entire collective of the "GSJP Plant", the work began; the first designs of engines, rockets, missiles, and experimental apparatus were converted into metal and put into use on the ground and in the air. Not only was the immediate goal successfully realized, but a vast effort was started to achieve the principal and long-term goals. The successes of the GSJP in the area of liquid-propelled rockets and oxygen LPRE, together with the achievements of the Gas Dynamics Laboratory (GDL) in the area of gunpowder missiles and nitric acid LPRE, were the deciding factor in the organization of the Scientific Research Institute of Jet Propulsion (SRIJP). The personal contribution of Korolev in this matter was even then highly valued. In relation to the organization of the SRIJP, by the decision of the Bureau of the Presidium of the Central Committee of the Osoaviakhim, Korolev was decorated with a medal "for outstanding performance in the Osoaviakhim" [9]. He was then named the assistant head of the SRIJP and obtained the title of division engineer.

I would like to note that this was not only the contribution of an organizer, but also the contribution of a scientific director and a direct participant in the outlining of most of the objectives of the GSJP at all stages of these studies, from the origin of the

concept to the final experiments. In this case, Korolev always took on himself the solution of the most important problems, but these problems were not always very interesting from the creative point of view.

While he was directing the entire operations of the GSJP, and solving a host of related problems, Sergey Pavlovich never broke off from his favorite creative theme, that of a manned flight on a rocket aircraft, where his talents could be used most completely, as well as his knowledge as an aircraft-designer. After Tsander's, Tikhonravov's, and Pobedonostsev's teams had been organized, Korolev organized yet another special team for designing winged rocket apparatus. He suggested that the head of this team be an experienced aviation specialist, such as I.A. Zheleznyakov or A.V. Chesalov. But seeing that they were not as fascinated with the idea of a manned rocket flight as he himself was, Korolev left the immediate directorate of the fourth team to himself. In addition to continuing his studies with the RP-1, studies also began on more contemporary designs of rocket aircraft (RP-2 and RP-3) and on the problems of producing unmanned winged rockets (Theme 06). /11

The most expansive scientific research and design construction activity of Korolev in this direction developed during the years when he worked at the SRIJP (1934-1938). It is true that at first the studies on rocket aircraft were not included in the plan of the Institute, since the flight of the RP-1 had not been realized because the OR-2 engine was not perfected to the necessary degree.

On the basis of the experience of the GSJP, Korolev agreed that the rocket aircraft would not be included in the plan of the Institute; he then added that, in order to produce oxygen LPRE in the SRIJP, two teams would have to start immediate operations in parallel directions.

"For every researcher, for every worker in this area", Korolev wrote in his book, "the motor should be the center of attention. All the other problems, even the most complex ones, will undoubtedly be solved in time rather completely, during the process of working with aircraft models and with the entire assemblies (and they will surely fly if there is a reliable engine)" [5, p.66]. While calling for a concentration of attention on the problem of producing a perfected motor, Korolev himself nevertheless did not train himself in engineering but continued to study the problem of producing a rocket aircraft within a complex, concentrating his attention on winged rockets.

Such a selection for the direction of his studies can be explained by the fact that the use of wings on military rockets gave roughly 5 times greater range than that of ballistic rockets with the same launching weight. With equal range, the winged rockets could carry significantly greater payload. At the same time, air defense was then rather undeveloped: only the very first experi-

ments had been made in the area of radar, non-contact detonators, and other effective means of air defense. Therefore, the low velocity of the winged rocket in approaching its target was then not a serious deficiency. The winged rocket was easier to control in flight with the aid of instruments similar to automatic pilots. /12 Moreover, Korolev counted on using his experience in working with winged rockets for working with rocket aircraft.

The first Soviet winged rocket 06/I, produced in the GSJP, completed its first flight on May 5, 1934. It flew for about two hundred meters. In 1935, small winged rockets and their models took off one after another. Korolev's right hand in all these studies and designs was Ye. S. Shchetnikov. An important role in all this work belonged to the designer of the first Soviet rocket gyroscopic automatic stabilizers and regulators, S.A. Pivovarov, whom Korolev had prepared specially for this role back in the GSJP. The young engineers M.P. Dryazgov, B.V. Raushenbakh, and A.V. Pallo worked with enthusiasm to bring Korolev's ideas into being.

In designing the winged rockets, the most complex problem for a long time remained the stability of their flight. Korolev decided to turn to the aid of specialists in the area of the mechanical and mathematical sciences. In 1936, at one of the meetings of the Scientific Research Institute of Mechanics of Moscow State University, he gave a detailed lecture on studies on winged rockets, and described to the scientists the task of investigating the motion of uncontrolled and controlled rockets and finding means to guarantee the stability of their movement. As a result, it was agreed that a group of young mechanics and mathematicians of Moscow State University would begin research on technical problems provided by the SRIJP. This was the first case of involving the forces of pure science in the solution of the practical problems of rocket technology.

By 1936, the engineers of the SRIJP had developed several LPRE's which satisfied the requirements imposed. The best of them were the oxygen LPRE 12/K with a thrust of 300 kg, and the nitric acid LPRE ORM-65 with a thrust of 150 kg. The design of the engines also accelerated the pace of studies with rocket aircraft. For this purpose, a new (5th) division of the SRIJP was established, with S.P. Korolev as the head. As a result, in 1936, a long-range winged rocket (Type 212, "ground to ground") with a flight range of 80 km was developed, as were a similar rocket, (Type 201, "air to ground") and a zenith rocket, 217, directed along the beam of a searchlight. Several designs of ballistic rockets, including those for investigating the stratosphere, were also developed. All these rockets were prepared and began to undergo terrestrial tests and flight experiments.

How was the rocket aircraft doing? Sergey Pavlovich's thoughts /13 did not stray from it for one minute; he continued to study the

problem of a rocket aircraft independently, according to the standard procedure.

On April 5, 1934, at an All-Union Conference on the Study of the Stratosphere called by the Academy of Sciences of the USSR, he delivered an article in which he exposed the problems standing in the way of a realization of a manned rocket flight [10]. At the end of the same year, he began to design his new glider SK-9, which was intended for operation with an LPRE. In the autumn of 1935, with the aid of the Osoaviakhim, the glider was constructed at the Moscow Glider Plant in Tushina. Long and varied experiments showed its excellent flying qualities and the suitability of using a rocket engine in it.

In March, 1935, by the initiative of S.P. Korolev, the SRIJP and the Aviavnito called for an All-Union Conference on the Use of Powered Aircraft in the Conquest of the Stratosphere. Korolev presented an article at this conference which was entitled "A Winged Rocket for Manned Flight", in which he presented the results of his research. He was the first to describe the characteristics and possible design of a rocket aircraft, its designed weight analysis, and an analysis of its flight characteristics. In the article, he mentioned the task of establishing a rocket-aircraft laboratory for flights of a purely experimental nature at low altitudes, by which "it would be possible to conduct a systematic study of the various rocket apparatus in the air. This would make it possible to conduct the first experiments with an air-breathing jet engine and a large number of other experiments, keeping the aircraft initially at a low altitude" [11, p.56]. It was this very kind of apparatus into which Korolev wanted to convert his glider SK-9.

In the conclusion of the article, Korolev said: "A winged rocket has great significance for high-altitude manned flight and for investigating the stratosphere. The task for the future is that by persistant daily work, without excess commotion and publicity (as is unfortunately still characteristic of a large number of studies in this area), we might master the principles of rocket technology, and be the first to reach the heights of the stratosphere and ionosphere" [11,p.56].

In 1936, studies on rocket aircraft were included in the plan of the SRIJP. In June, 1936, the Technological Council of the SRIJP examined the design of the experimental rocket aircraft made by Korolev, and the program of immediate studies. It was resolved that the "Divisions of the Institute should view their work on Goal 218 in the plans for 1937 as one of the leading studies of the Institute" [12].

In 1938, the SK-9 glider was brought to the Institute, where /14
the rocket engine apparatus with the LPRE ORM-65 was installed in it. The machine was called "RP-318" and was to serve as an experimental laboratory for checking and analyzing the ideas included in

the design of the rocket aircraft. At the end of the year, fire tests began on the engine apparatus installed in the glider. Dozens of experiments were conducted [13].

In February, 1938, in the article "Scientific Research Studies on Rocket Aircraft" [14] prepared in collaboration with Shchetnikov, Korolev first clarified the purposes of rocket aircraft and the rational ranges for their use, and formulated the principal tasks of long-term study. The idea of producing a fighter-interceptor and an experimental aircraft for investigating the stratosphere and the aerodynamics of high velocities was scientifically founded. A four-stage design program for such an aircraft was proposed: an original version, in which the results already achieved in the SRIJP would be entirely re-created (for launching from the ground, it should reach an altitude of 9 km; for launching from an altitude of 8 km it should reach an altitude of 25 km); a modified version for a longer flight; a record-breaking version; and a long-range version. This aircraft should reach altitudes of 53 km during the rocket flight if launched from a mother plane.

Much in this draft anticipated what has become characteristic of experimental craft in our time.

In 1939, a new, more perfect rocket engine (RDA-I-150) was installed on an SK-9 glider; on February 28, 1940, the first Soviet manned flight, piloted by V.P. Fedorov, was made with an apparatus with a rocket engine.

The successful flight of the RP-318 resulted in renewed attention to studies of rocket aircraft at the Institute, and a number of other creative groups also became very interested in the problem of rocket aircraft. As early as 1942, the first Soviet rocket fighter, the BI-I, designed under the direction of V.F. Bolkhovitinov, completed a successful flight.

The above shows that the role of S.P. Korolev in the origin and establishment of Soviet rocket technology, which is a very important part of universal rocket technology, was so great that it is difficult not to see it. He made a great contribution as a propagandist and popularizer of rocket technology, as an educator of rocketry-trainees, as an organizor and director of the principal Soviet rocketry organizations, as a scientific researcher, and as a designer; he was an outstanding specialist in the developing field of rocket aircraft. /15

The scientific research work of Korolev in this direction provided the design of piloted rocket apparatus with a solid scientific basis and led to the successful flight of a rocket aircraft with an LPRE.

Another achievement connected with the name of S.P. Korolev is no less significant. The development of modern rocket technology

in its initial stages followed two approaches: aviation and artillery. Due to the scientific and technological activity of Korolev, these two approaches were combined and the winged guided rockets of his design were the first in which rocket technology followed a path devoted specifically to rocketry.

A great many very different people created Soviet rocket technology during this period (1930-1941). Among them were brilliant designers, perspicacious theoreticians, ardent propagandists, strong organizers, daring experimenters, people with great initiative, and may unfailing performers. They were all regular enthusiasts of rocket technology, and each one made his large or small contribution. But Korolev's outstanding contribution and his leading role are explained by the fact that he was all of these in one person.

All of his qualities as a creator and scientist, tempered and refined in the constant purposeful struggle for the development of rocket technology and astronautics, predetermined the outcome that the Soviet people and the Communist Party entrusted him with the leading role in the development of rocket technology and astronautics at the crucial stage. Sergey Pavlovich Korolev was able to cope with this most complex task as well. His name has been written in the history of human progress as that of the founder of practical astronautics.

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THE PRINCIPAL CHARACTERISTICS AND DESIGN FEATURES OF R. GODDARD'S ROCKETS

I. N. Bubnov

ABSTRACT: The article presents the principal contributions of Robert Hutchings Goddard (1881-1945) in the USA in the field of liquid propellant rocket engines. The principal improvements made by Goddard were related to the combustion chamber, the system for feeding the fuel, the stabilizing system and the mass-flow function. His improvements were not systematic, according to the author, because of the limited support of the US Government, and the secrecy which surrounded him. It is shown that, although Goddard's rockets lagged behind those designed in Germany in their scale-ratio, the experimenter did make an outstanding achievement in stabilizing a rocket with jet-and air-vanes, and in using a pump-line system for feeding the fuel.

At the end of the 1920's and the beginning of the 1930's, the /17 basic principles of using liquid propellant rockets, first formulated by Tsiolkovskiy and later by Oberth and other scientists, were greatly expanded in a number of countries. With the appearance of the first flying models during these years, the foundations of modern rocket technology essentially began to be established.

The studies of the first researcher and experimenter in the USA in this area, Robert Hutchings Goddard (1882-1945), were one of the most outstanding contributions at this stage in the origin of liquid propellant rockets.

Goddard's principal merits lie in the fact that he was the first to design an efficient liquid-propellant rocket engine and to conduct experiments with it before the stage of flight experiments, and the first in the world to complete the launching of a liquid-propellant rocket (March 16, 1926).

An important achievement of Goddard's is the fact that he was one of the first (in the first half of the thirties) to give a practical presentation of (and to partly solve) all the technological and experimental problems of that time in designing a high-altitude liquid-propellant rocket. These problems were the following: supplying the fuel components from the tanks to the engine, selecting the weight-ratio of the components, spraying the fuel into the combustion chamber (spray burner), cooling the walls of the chamber and the nozzle, the resistance and heat-insulation of the tanks,

stabilization of the rocket during flight, aerodynamics of the rocket, preserving the structure after launching, starting of the engine, organizing ground firing tests, measuring the characteristics of the engine and the parameters of the flight trajectory, etc.

Goddard made his most substantial achievements in developing the rocket's stabilizing system (with the aid of a gyroscopic transducer, air- and jet-vanes with servodrive), and, at a later stage of studies (1939-1941), in producing a pumping system for supplying the fuel. Certain other technological achievements of Goddard are also of interest: the organization of a system for supercharging the tanks, a spray with many spray burners, tubular casings for cooling the combustion chamber and the nozzle (one of the fuel components), etc. /18

In the 1930's, most of the enthusiasts of rocket technology in various countries, considering the novelty and the complexity of the problems in constructing liquid propellant rockets, joined groups and societies for the purpose of conducting experimental studies more effectively. In this case, the countries which achieved the greatest successes at the beginning state of rocket technology were the Soviet Union and Germany, i.e, those countries in which rocket research had government support. Another characteristic of this period was the limited (for objective reasons) exchange of information between individual researchers and groups, which led to parallel studies and a significant waste of effort in solving problems which had already been solved by other researchers.

From these points of view, Goddard's studies differed in their originality. Throughout almost the entire course of his activity, Goddard worked on relatively small funds which he occasionally obtained from private parties. However, Goddard skillfully limited the number of his collaborators, both quantitatively and qualitatively. Goddard's small group consisted mainly of technological experimentors who merely carried out the ideas of Goddard himself. Moreover, Goddard worked in a secretive situation, almost excluding an exchange of information with other researchers, and the results of his studies were published only in general outlines at a significantly later time. Goddard even isolated himself from the experimental group of the American Rocketry Society, of which he was selected as a director-member. As a result, the members of this group developed rockets according to designs which were mainly borrowed from German rocket-designers.

These characteristics were hardly the principal reason why Goddard, who began his experiments with LPRE's and liquid propellant rockets many years earlier than others (in 1920), and who described (in general outlines) a reliable method for designing high-altitude experimental rockets, wasted a significant part of his lead, even in the middle of the thirties, and lagged behind other researchers, not only in the depth and range of his studies, but also in the characteristics of the engines and rockets which he developed.

Thus, for example, an LPRE with a thrust of 150 and 300 kg (ORM-50 and ORM-52 [4]) was produced in the Soviet Union in 1933. The maximum thrust of Goddard's LPRE's during the same year did not exceed 122 kg. In 1935, an LPRE with a thrust of 1500 kg was produced in Germany (for Goddard, it was 285 kg). Even at the

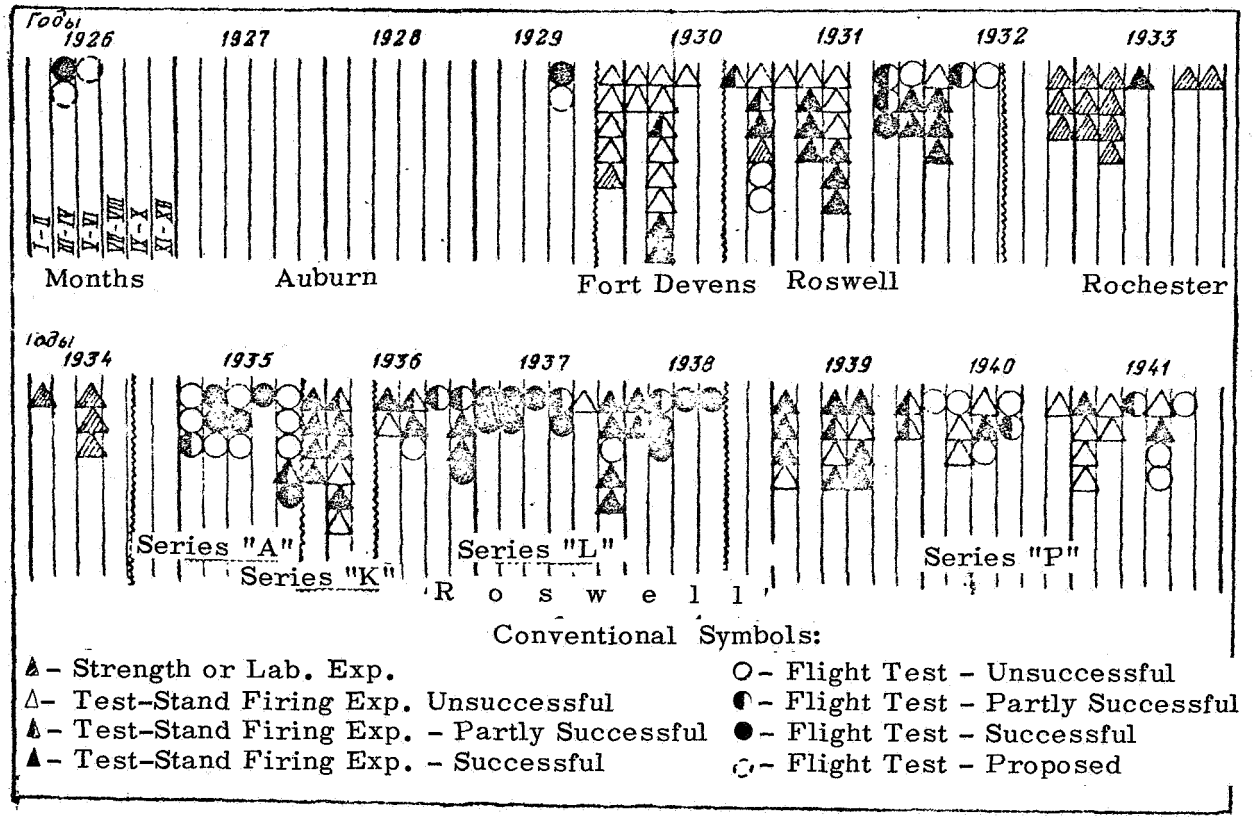

Fig. 1. Diagram of the Distribution (by Years) of Goddard's Static and Flight Tests with Liquid Propellant Engines and Rockets. /19

beginning of the Thirties, LPRE's were being tested in the Soviet Union and in Germany, using various fuel components. Goddard used only one type of fuel in all his engines and rockets: liquid oxygen and gasoline. In 1937, the Germans produced the A-3 rocket, with a launching weight of 750 kg [5], while the maximum launching weight of Goddard's rockets had reached only 340 kg in 1941. Moreover, Goddard was late in analyzing the problems of the practical use of liquid-propellant rockets: except for rare exceptions, no payload was established for the models he developed. /20

Goddard did not succeed in realizing many of his fruitful ideas. Most of his technological discoveries and achievements remained

beyond practical realization. The ultimate influence of Goddard's achievements on the development of rocket technology in the entire world, as well as in the USA, was very small. Governmental developments in the field of rocket technology in the USA began, in fact, only in the year that Goddard died, and the reason for this new stage was the achievements of German rocket-designers.

In the articles Goddard published [1,2,3], there is no analysis of the energy characteristics of the rockets he built. All his attention was concentrated on achieving efficiency of the structures. Even today, we still do not know of any scientific analysis of his achievements made in the USA or in other foreign countries. In our country, there is also very little known about Goddard's studies, and none of his books have been translated fully into Russian.

If we do not consider his first rocket (1926) (whose launching was followed by a long delay in Goddard's studies, and about which information is rather scarce), the actual evolution of Goddard's rockets lasted from 1929 to 1941. From the end of 1941, due to the USA's entry into the Second World War, Goddard had to cease his experiments and serve with the US Navy, where he studied the production of LPRE's for accelerating launching.

As we can see from the diagram shown in Figure 1, Goddard conducted 155 experiments with liquid-propellant engines and rockets from 1926 to 1941. Fifty of these experiments (or 32.3%) were flight tests with different types of rockets, 87 (or 56.1) were static firing tests with almost completely assembled rockets, and the remaining experiments were resistance or laboratory tests with structural elements. Moreover, there is some unconfirmed information on three flight tests and one other static firing test. However, there are absolutely no data on statistical experiments conducted before the autumn of 1929. /22

Out of 87 static firing tests, 42 (or 48.3%) were completely successful, i.e., the engine's combustion chamber developed the propulsion, operated for a sufficient amount of time to determine the characteristics, and did not burn out. Nine experiments were partly successful, i.e., some of the characteristics were determined, but the chamber burned out or stopped supplying the fuel. The completely unsuccessful experiments made up 41.4% of the total number of static tests.

Out of the 50 flight tests, 19 (or 38%) were completely successful, i.e., the rocket took off from the launching tower and climbed, passing through an active segment which was close to the calculated one. A burnout of the chamber after this was not reflected in the evaluation of the final result of the launching. Ten flight experiments were partially successfull, i.e., the rocket took off from the launching tower but the active segment was not maintained for some reason. Together with the completely successful launchings this made up 58% of the total number of flight tests. Obviously, such results should be very valuable.

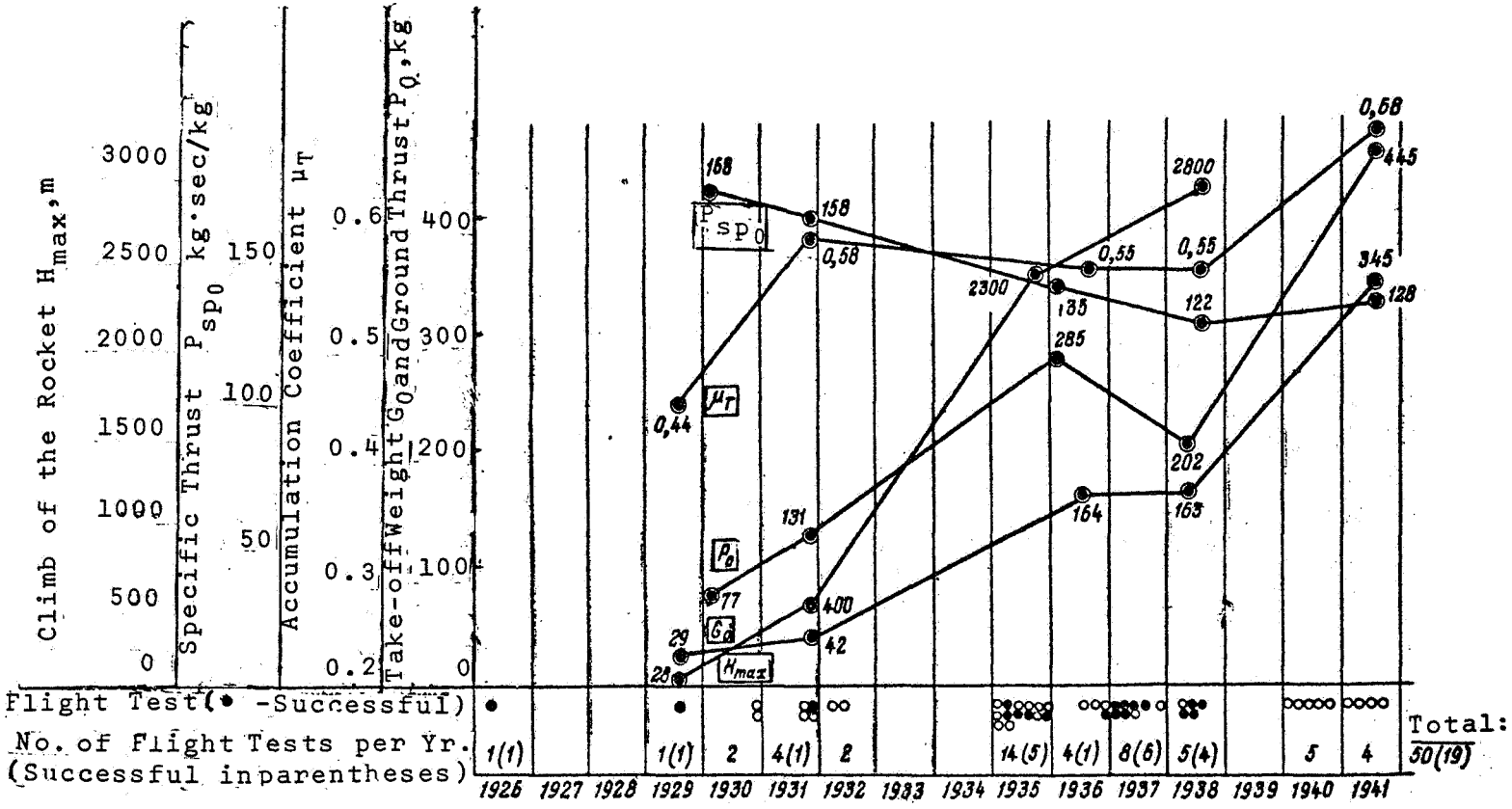

Fig. 2. The Change during the Years in the Principal Parameters of Goddard's Rockets.

Twenty-one flight tests did not meet with success. Most of the failures were connected with a premature burnout of the chamber or with insufficient propulsion of the engine. Note the lack of explosions of a rocket on the launching or test-stand devices. Explosions of a rocket in flight were also very rare.

Figure 2 shows the distribution of the flight tests and the change in certain characteristics (launching weight, maximum thrust on the ground, specific thrust, rocket altitude, and the accumulation coefficient) by years. The numbers at the bottom of Figure 2 show the total number of attempts at launching for each year, and the numbers in the parentheses show the number of completely successful launchings. As we can see, Goddard conducted flight tests in large series, of which those conducted in 1935 and in the winter of 1936-1937 were particularly significant.

I would like to point out the consistent increase of the launching weight from 30 kg to 345 kg. In this case, the accumulation coefficient of the rocket, $\mu_T = G_F/(G_0-G_{p.l.})$ where G_0, G_F, and $G_{p.l.}$ are the take-off weight, the weight of the fuel, and the payload weight, respectively), greatly increased at the beginning, due mainly to the transition to thin-walled welded tanks. For a long time, it remained practically unchanged, as a result of an increase in the weight of the structure due to the installation of a rocket-stabilizing system. At the final stage of his activity, Goddard succeeded in obtaining a very high value of μ_T, because of /23 a large-scale increase in the size of the rocket and a special lightening of the structure.

A certain decrease in the specific thrust of Goddard's rockets can be partially explained by the following reasons: (1) Increasing the engine thrust because of the dimensions of the chamber, and lightening the latter, Goddard could not also greatly increase the pressure inside the chamber; (2) Fearing burnouts of the chamber, Goddard attempted to operate at low coefficients for an excess of the oxidizer and at low temperatures in the chamber; (3) The increase in the thrust of the engine was achieved primarily because of an increase in the exhaust velocity, and not because of the mass flow of the fuel (in relation to the difficulties of obtaining a high pressure in the fuel-injection system).

The Table shows some principal characteristics of Goddard's rockets which were obtained by various methods: from direct information on a given launching, indirectly (according to the information on other launchings), by calculations, and also by assumptions. In the calculations, special attention was given to the well known relationship between the specific thrust and the total impulse.

For a criterion of the structural perfection of the rocket, we took the coefficient η, the ratio between the ideal kinetic energy (which could be obtained for the rocket after determining the fuel reserve) and the entire energy of the fuel reserve:

Principal Characteristics of Goddard's Rockets

/24

No.	Date of Experiment	Designation of Experiment	Type of Experiment	Launching Weight G_0, Kg	Dry Weight G_{dry}, Kg	Fuel Weight G_F, Kg	Payload Weight $G_{p.l.}$, Kg	Average Thrust on ground, P_0, Kg
1.	7/17/29	--	Flight	25.9	14.5	8.4	--	≈ 43
2.	12/10/30	--	Static	24.4	15.2	9.2	--	≈ 45.4
3.	5/23/31	--	Static	28.0	≈ 15.6	12.4	--	53.8
4.	5/28/31	--	Static	29.0	≈ 15.5	13.5	--	66.8
5.	11/23/31	--	Static	29.0	≈ 15.4	13.6	--	90.0
6.	12/23/31	--	Static	33.5	≈ 18.1	15.4	--	47.5
7.	1/26/32	--	Static	31.9	≈ 18.1	13.8	--	82.5
8.	2/11/32	--	Static	29.7	18.1	11.6	--	80.8
9.	6/18/36	L-2	Static	163.3	88.0	75.3	4.3	≈ 200
10.	7/16/36	L-4	Static	134.7	61.2	73.5	4.3	229
11.	10/3/36	L-6	Flight	109.6	68.8	40.8	3.8	≈ 220
12.	1/14/37	L-11	Flight	67.6	46.3	21.3	≈ 2.0	≈ 82
13.	7/28/37	L-16	Flight	63.5	42.2	21.3	≈ 2.0	≈ 100
14.	11/12/37	L-20	Static	78.2	36.5	41.7	≈ 2.0	103
15.	12/18/37	L-22	Static	72.1	33.1	39.0	--	117
16.	2/2/38	L-25	Static	85.0	≈ 36.4	48.6	--	206
17.	2/9/40	P-15	Flight	334	107	227	7	≈ 350
18.	7/17/41	P-33	Static	216	115	101	7	375
19.	1944-49	"V-2"	Flight	13.0T	4.2T	8.8T	1.0T	27T
20.	1958-61	"Thor"	Flight	50.1T	4.7T	45.4T	0.8T	72T

Designations Used:

14.5 - Known Parameters
15.6 - Parameters Taken on the Basis of Indirect Data
29.0 - Calculated Parameters
43.0 - Assumed Parameters

Principal Characteristics of Goddard's Rockets (con't)

Time of Engine Operation, t, sec.	Total Impulse I_Σ, Kg sec.	Specific Thrust $P_{sp.0}$, $\frac{(Kg \cdot sec)}{kg}$	Accumulation Coefficient M_T	Relative Payload Weight, $G_{p.l.}$	Mass Ratio, Z	Average Exhaust Velocity, W, m/sec.	Ideal Velocity, V_{id}, m/sec.	Energy Coefficient, η
18.5	795	94.8	0.324	---	1.78	930	539	0.0272
~ 20	908	98.8	0.377	---	1.60	970	455	0.0185
21	1130	91.0	0.443	---	1.80	895	525	0.0188
19	1270	94.2	0.465	---	1.87	923	578	0.0208
24	2160	158	0.469	---	1.88	1550	978	0.0586
31	1470	94.5	0.460	---	1.85	927	570	0.0208
19	1565	113.5	0.433	---	1.77	1115	633	0.0285
20	1615	139	0.390	---	1.64	1365	675	0.0386
36	7165	95.2	0.473	0.026	1.86	~ 933	575	0.0224
28	6410	87.3	0.565	0.032	2.20	855	673	0.0204
~ 20	4400	108	0.386	0.035	1.60	1060	498	0.0226
20.6	2050	96.3	0.324	0.030	1.46	945	357	0.0150
~ 30	3000	141	0.346	0.032	1.51	1380	569	0.0346
49.9	5140	123	0.547	0.026	2.14	1208	921	0.0403
30.5	3565	91.5	0.541	---	2.18	898	696	0.0223
29.6	6075	125.0	0.572	---	2.34	1275	1085	0.0478
65	22700	~100	0.680	0.021	3.12	980	1115	0.0318
34	12750	126	0.484	0.032	1.88	1245	791	0.0386
70	$1.89\ 10^6$	215	0.733	0.077	3.10	2110	2390	0.161
165	$11.9\ 10^6$	262	0.921	0.016	10.7	2570	6080	0.207

$$\eta = \frac{Q_{kin}}{Q_{heat}}$$

In this case, the kinetic energy of the rocket is calculated according to the ideal velocity, which in turn is determined according to Tsiolkovskiy's formula:

$$\eta = \frac{(G_0 - G_T)V_{id}^2}{2gKq_TG_T}$$

where q_T is the caloric value of the fuel (for the liquid oxygen and gasoline used by Goddard, it is 2200 Kcal/kg), q is the acceleration of the force of gravity, K is the mechanical equivalent of the heat.

For convenience in the calculations, we can write the formula for η in another way:

$$\eta = \frac{(1/\mu_T - 1)\left(W\rho n \frac{1}{1-\mu_T}\right)^2}{2q_TgK}$$

where W is the exhaust velocity.

As we can see from the table, the coefficient η of Goddard's rockets increases rather insignificantly in time. This confirms the fact that Goddard paid little attention to energetic perfection of his rockets, concentrating his efforts on producing efficient rockets which would be reliably stabilized in flight. For comparison, the table also shows the characteristics of later rockets, the German "V-2" and the American "Thor". /26

Conclusions

(1) During the period 1929-1941, Goddard conducted an intensive study (with short interruptions) of the design of a liquid-propellant rocket. The improvements were made mainly in order to obtain a rocket which was efficient in all its principal elements and systems: the combustion chamber (shape, size, spraying of the fuel, cooling, etc.), the system for feeding the fuel (the operational heat in the supercharger system, regulation of the pressure in the feed and flow of the fuel), the stabilizing system (the control element, the regulating devices, servodrive), the mass-flow function and aerodynamics, the system for retrieving the rocket, the launching devices, the test-stands, and the trajectory-tracking system.

(2) The limited means and small staff of collaborators did not allow Goddard to conduct any systematic theoretical research together with the experimental, purely empirical study, or to make systematic improvements of the rocket characteristics.

(3) The maximum launching weight of Goddard'd rockets was 340 kg in 1940, i.e., he lagged far behind the rocket-designers in Germany (for example, in the scale-ratio of the rockets). At the same time, Goddard's rockets were not inferior to the rockets of other countries in their degree of perfection.

(4) One of Goddard's most important achievements was the designing of a gyroscopic system for stabilizing the rocket with jet- and air-vanes as acutating organs and compressed-air drive.

(5) Goddard's other most important achievments were the transition from a system to a pump-line unit. In his own experiments, Goddard exhausted the possibilities of the fuel-injection system; he increased the pressure in the system to more than 25 kg/cm^2, when the weight of the structure should have increased substantially for stability reasons.

(6) The launching weight of the rocket was increased faster /27
than the thrust of the engine apparatus. As a result, the launching thrust-weight ratio of Goddard's rockets decreased from 3-5 to 1.25-1.5; this made it possible to decrease the weight of the structure, due to the decrease in the overload.

(7) Goddard could not obtain a substantial increase in the exhaust velocity, despite the relatively high pressures in the combustion chamber. The reason for this can be found in the selection of a relatively ineffective fuel, the low degree of expansion of the combustion chamber nozzle, and the low weight ratios of the fuel components,i.e., the low temperatures in the combustion chamber. Goddard did not obtain more than 60% of the maximum possible specific thrust for the given pressures.

(8) The social and historical conditions under which Goddard worked did not allow this outstanding experimenter to maintain his priority in the field of designing LPRE's and liquid propellant rockets. The greater part of Goddard's technological achievements did not find a successful realization in actual rockets. As a result of this, and also as a consequence of the secrecy which cloaked Goddard's work, the effect of his studies on the development of rocket technology was small, not only in the entire world, but also in the USA. The American government, which turned a deaf ear on Goddard's propositions for many years, found it necessary at the end of the Second World War to begin its rocket design program with the achievements of German rocket designers.

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THE CONSTRUCTION OF AN ELECTRIC ROCKET ENGINE IN THE GAS DYNAMICS LABORATORY

L. M. Aleksandrova

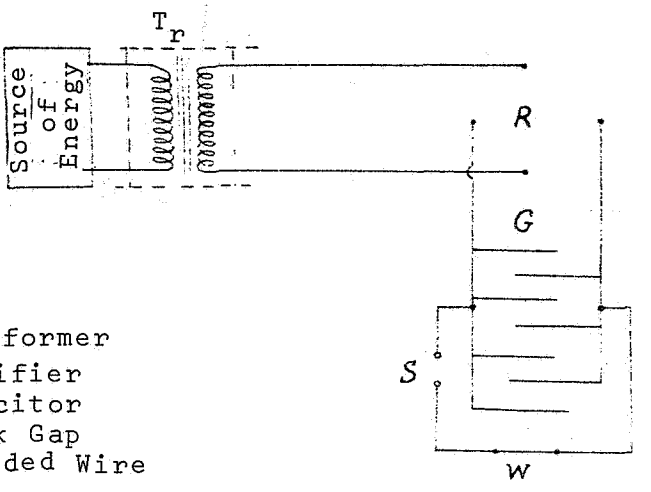
ABSTRACT: Based on an article dated April 18, 1929, "Metal as an Explosive. A Rocket Engine with a High Exhaust Velocity", the Gas Dynamics Laboratory undertook the design and production of the first electric rocket engine of the electrothermal type. The first designs were based on the principle of exploding metal wires for the discharge. The article shows that studies are still being conducted on the problem of sources of energy for such an engine.

On April 18, 1929, the scientific article "Metal as an Explosive. A Rocket Engine with a High Exhaust Velocity", dated April 10, 1929, was presented as an invention to the Military Scientific Research Committee of the Revolutionary Military Council of the U.S.S.R. [1]. /29

I would like to mention that, as a result of studying the materials in the Archives for the period 1929-1933, and the sources in the literature, I can maintain that the article "Metal as an Explosive", was the first theoretical work where the principle of the function of an electric rocket engine of the electrothermal type was presented, and where the necessary calculations were given.

The principle of the function of this engine was based on the thermal effect of the current: fine metal wires explode in the chamber of the ERE (electric rocket engine) with the aid of brief high-power pulses of electric current (at the end of 1929, liquids which conducted electricity were also tested for use as the working substance for ERE's); as a result of the explosion, the conductors heat up almost immediately, to a very high temperature, and convert from a solid or liquid state to a gaseous one. The gaseous products obtained from the electric explosion discharge through the nozzle at a very high velocity [1].

The principal electric circuit of the ERE of the electrothermal type has the following appearance:



Tr - Transformer
R - Rectifier
G - Capacitor
S - Spark Gap
W - Exploded Wire

/30

The merits of the author of this article involve the fact that he dared to make a creative approach to the well known studies at that time on the problems of the electric explosion of metals, and he dared to apply these electric explosions to rocket engines.

The articles of Schuster and Helmzalech, in particular, were used in developing the electric rocket engine. They studied the spectrum of metals during an electric explosion in order to determine the rate of displacement of the metal vapors [2]. The researchers also used the studies of Anderson, who in 1919 conducted an electric explosion of metal wires both in the atmosphere and at decreased pressure, in order to examine the spectra of the metals (specifically iron) at high temperatures.

According to the data of Anderson, the temperature of the gases after the electric explosion of the metals reached 20,000°C, while the rate of diffusion of the metal vapors in the air was about 3.3 km/sec [3].

In 1925-1926, Anderson and Smith published additional results of their experiments, in which they studied the change in the resistance of metal wires during an explosion, as well as the temperature [4,5]. /31

The problem of the electric explosion of metals was of great interest to a specialist, because it was possible here to control the amount of expended energy and matter separately, which was completely unfeasible in chemical reactions. The temperature of gaseous products, under the conditions of an electric explosion, can change within a very broad range, in relation to the amount of energy expended per unit mass of matter; the greater the energy, the higher the temperature (and therefore the vapor pressure), at

which a more effective operation can be accomplished.

The temperature, gas formation, and pressure during the explosion were examined in detail in this article, and serious conclusions were drawn on these problems.

On the basis of the theoretical assumptions presented in the article, practical requirements were also imposed on the explosives: (1) greater heating efficiency; (2) greater gas formation; (3) greater specific weight, and a number of other requirements.

A reference table was presented at the conclusion of the article. Data which gave the metals definite characteristics as explosives were classified in this table.

It is very difficult to make a brief summary of the content of the article "Metal as an Explosive". This requires a special analysis. This article was approved by experts, Professor M.V. Shuleykin and the Director of the Gas Dynamics Laboratory (GDL), N.I. Tikhomirov. Its author was given the possibility of conducting practical studies on the design of an electric jet engine.

On May 15, 1929, in a specially established subdivision (which will be called Division P) of the Gas Dynamics Laboratory in Leningrad, studies on the designing of the ERE were begun. Research on the designing of LPRE's was conducted parallel to these studies.

Originally, the GDL subdivision for designing and testing ERE's was located in the high-voltage laboratory of Academician I.A. Ioffe at the Institute of Electrophysics in Lesno (near Leningrad) in 1929-1930. In 1932-1933, studies of the ERE's were conducted on the territory of the Ioannovskiy Ravelin of the Peter-Paul Fortress.

On the basis of examinations of the original archival materials /32
of the Gas Dynamics Laboratory, we can conclude that Division P of the GDL took the right direction in designing the ERE's: various pulse circuits were analyzed and tested; a series of experiments were conducted in order to clarify the properties of the gases as explosives; a number of studies were conducted for selecting the working substance for the electric rocket engine, both with wire and with conducting liquids; special devices (carburetors) for feeding the conducting liquids or metals into the engine were designed and tested; a number of equally important studies were made.

The studies with the carburetors should be mentioned in particular. These were the first practical developments in the world related to the problems of supplying the working substance into the chamber of the engine.

During the period from October, 1929 to January, 1930, Division P of the GDL developed 3 types of carburetors: liquid, mercury

and wire. In March, 1930, reports were made on the universal liquid carburetor of the laboratory type [6,7,8,9]. In the liquid and mercury carburetors, the conducting liquids or mercury were supplied from the tank through capillary tubes with interchangeable adapters of various diameters. Water oxidized with copper sulfate ($CuSO_4$) or nitric acid (HNO_3) was also used (in addition to mercury) as the explosion liquid, as were other liquids. According to the results of the studies, a number of reports were published [10,11].

The feed mechanism in the wire carburetor consisted of two steel cylinders which had a directing device for feeding the wires. The cylinders were rotated by an electric motor (1/32 HP; n = 3000 rpm; 110-120 V) through a reducer. Metal wires (tungsten, copper, etc.), as well as carbon filaments, were used in the wire carburetor as working substances. For normal operation of the carburetor, the frequency of explosions reached 25 per second. The explosion processes in the metals or conducting liquids were photographed with movie cameras through a light filter.

In the studies in the GDL, a transformer apparatus made by the "Burevestnik" plant was used in the pulse circuit at 100 kV, 10 kVa, along with 4 kenotrons and oil-filled high-voltage capacitors for 40 kV, with a capacitance of 4μ.

On March 23, 1931, the author of the article "Metal as an Explosive", submitted an application to the Comittee for Inventions for an invention entitled "Rocket Engine", and obtained a copyright [12]. /33

It was shown in the application that an electric jet engine could be used "for aircraft launched from the ground". It was also shown that the subject of the patent was a "jet engine characterized by the use as a waste product (exploded in the combustion chamber with the aid of an electric discharge) of any conducting substance".

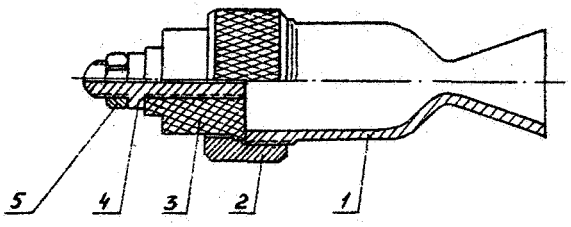
Various methods for operating the engine were proposed:

(1) The substance for the electric explosion is fed continuously into the combustion chamber.

(2) In the case of feeding a liquid substance for the electric explosion, the spray heaters for feeding the liquid are used as the poles of the discharge circuit.

(3) One of the poles feeding the apparatus is joined directly to the metal of the engine [13].

In 1932-1933, the design of the ERE was finally determined. It consisted of a chamber into which a wire, intended for the explosion, was fed. The spray heater for feeding the wire was also one of the poles of the electric circuit, and the body of the chamber served as the second pole. An insulator was placed between the spray heater and the chamber. The entire engine was 90 mm long.



1. Chamber
2. Nut
3. Insulating Sleeve
4. Spray Heater
5. Nut

The effect of a single electric explosion was examined in an experimental chamber with a nozzle suspended on a ballistic balance. In this case, it was confirmed that the exhaust velocities of the products of the electric explosion, despite the losses, can reach tens of kilometers per second. /34

Further studies on ERE's were conducted in Division P of the GDL; particular attention was given to designing liquid propellant rocket engines (LPRE) as being the most necessary type (at that time) for practical use.

On the basis of examining archive and patent materials, as well as sources in the literature, we can draw the conclusion that the ERE which was developed and tested in 1929-1933 in the Gas Dynamics Laboratory of the Administration of the Military Institute, Science Division, of the Workers' and Peasants' Red Army was the first electric rocket engine of electrothermal type in the world.

The principal circuit diagram of the electrothermal rocket engine proposed in 1929 and developed in 1929-1933 is still not out of date. Such circuit diagrams can be used in modern engines for studying outer space, if the problem of producing the source for feeding them can be solved, as well as a number of other technological and structural problems affecting reliability and efficiency. It is well known that studies are now being conducted in this direction in the USA and in France [14-19].

The first ERE's which were used in the Soviet Union under real conditions of a space flight began their operation on the automatic station "Zond-2", which was launched on November 30, 1964, toward Mars [20]. The electric plasma jet engines installed on this station were intended for orienting the station in space. Somewhat earlier (on July 20, 1964) experiments were conducted in the USA with ion ERE's in a flight along a ballistic trajectory [21].

In September, 1965, the USA began using ERE's in space with the launching of the artificial earth satellite Vela, which had an electrothermal engine on board [22].

In the future, electric rocket engines should be widely used under the conditions of outer space (naturally, if a new method which is still unknown, has not been proposed for imparting pro-

longed and constantly-acting accelerations to a rocket in outer space).

At the present time, particularly in the light of the use of /35
ERE's, we are confronted with the problem of sources of energy for this type of engine. Naturally, it is inadvisable to take up the useful weight of a rocket with high-current pulse devices which use heavy sources of energy. It is possible that this will be an atomic electric station, a prototype of which is being produced by Soviet scientists ("Romashka"), or it could be a helium electric station or some other still unknown means of obtaining energy.

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AN ANALYSIS OF THE DEVELOPMENT OF AVIATION MODELING IN THE 19TH CENTURY

Yu. I. Novokshonov

ABSTRACT: The article examines certain regularities in the evolution of physical models of flying apparatus with a fixed supporting plane during the 19th century. The calculations presented show that the lack of horizontal empennage often found in the 19th century led to static "instability" of the models.

The modeling method is one of the basic methods of scientific /37
research. In science and technology, modeling should be examined from the point of view of the process of constructing and gradually perfecting a model of the given object.

The possibility of realizing a certain object in a combined material and technological form, as a working model, is of substantial significance. This possibility is particularly valuable under the conditions when (for some reason) there are no abstract, theoretical, mathematical representations of the object being examined. Naturally, under these conditions the model which can reproduce the characteristics and properties of the object mechanically is considered "best" [1].

It is of particular interest to analyze the historical evolution of models[1] of an object, considering the production of the corresponding complex of goals during the period of time being examined.

In the case being examined, such an analysis is particularly interesting in view of the fact that, over an extended period of time, the objective and technological methods (natural flying apparatus) adequate to the corresponding purposes was not realized, in connection with which the process of examining it followed the lines of physical modeling alone.

The working model of a flying apparatus which does not require great energy or regulation by a man during the experiment removed the danger to the latter, and, at the same time, showed broad possibilities of a gradual perfection of the model on the basis of experimental data. I would like to add that, in comparison with

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[1]Here, and in the future, by the term "model" we mean the material and technological copy of an object which reproduces some of its functions.

real apparatus, the model is cheaper and more simply prepared.

In the 19th century, the problem of maintaining stability of flight of a flying apparatus was one of the central tasks of aviation modeling. Three principal types of models were examined (classified according to the method for producing lifting power): /38

(1) Models with flapping wings.
(2) Models with a fixed supporting plane.
(3) Models with a rotating supporting plane (a rotor).

In this article, certain regularities in the evolution of models of flying apparatus with a fixed supporting plane are being examined.

Table 1 and Figures 1 to 9 show the principal, reliably-flown models of the 19th century. Certain structural differences in the aerodynamic schemes of the models are given in Table 1 in the vertical columns, and the differences in the means of propulsion and in the results of the experiments are given along the horizontal lines. The name of the researcher and the year of the experiments with the model are given at the places where the columns and lines intersect.

Of particular note is the fact that most of the 19th century models had a horizontal empennage, or spacing of the supporting plane along the axis ( )[2]. It is easy to show that these structural means are necessary and the only possible way of guaranteeing the longitudinal stability of the model.

Let us write the equation for the coefficient of the pitching moment of an apparatus without horizontal empennage:

$$m_{z,\text{-h.e.}} = m_{z_0,\text{-h.e.}} - (\overline{X}_{F,\text{-h.e.}} - \overline{X}_T)C_Y \qquad (1)$$

where $m_{z0,\text{-h.e.}} = M_{z0,\text{-h.e.}}/Syq$ is the coefficient of the zero pitching moment of an apparatus without horizontal empennage; $M_{t_0,\text{-h.e.}}$ is the zero pitching moment of an apparatus without horzontal empennage; S is the surface of the wing; V is the chord of the wing; q is the velocity head of the incident flow; $\overline{X}_{F,\text{-h.e.}}/V$ is the relative longitudinal coordinate of the focus of the wing in relation to the axis which passes through the leading edge; $\overline{X}_{F,\text{-h.e.}}$ is the longitudinal coordinate of the focus; $\overline{X}_T = X_T/V$ is the relative longitudinal corrdinate of the center of mass of the apparatus; X_T is the longitudinal coordinate of the center of mass.

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[2]Translator's note:... blank in text.

TABLE 1. MODELS OF FLYING APPARATUS WITH A FIXED SUPPORTING PLANE, SUCCESSFULLY TESTED IN FLIGHT IN THE 19TH CENTURY

	Models Without Engines		Models with Spring-loaded Rubber, and Pressurized Engines		Models with Steam and Gasoline Engines		Models with Rocket Engines	
	Stable Flight	Unstable Flight	Stable Flight	Unstable Flight	Stable Flight	Unstable Flight	Stable Flight	Unstable Flight
Models with horizontal empennage	Plin 1855		Penot 1871	Taten 1879	String-fellow 1848	Taten 1889		
Models with horizontal and vertical empennage			Julien 1858	Henson 1843	Du Tample 1855	Henson 1845		
Models with cross shaped horizontal and vertical empennage	Keily 1804		Mozhayskiy, 1876					
Models of the "Detached Plane" type	German 1893				Langley 1896			
Models of the "Flying Wing" type	Kotov 1896		Ewald 1861				Ewald 1886	

Note: Table 1 was constructed on the basis of References [2 to 8].

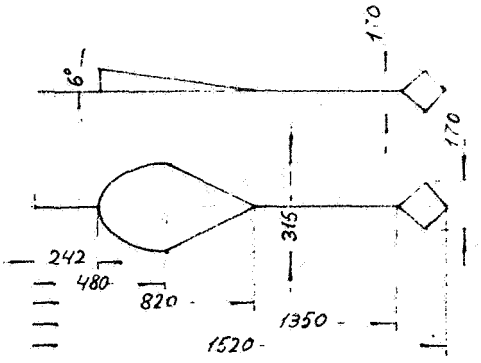

Fig. 1. Keily,1804

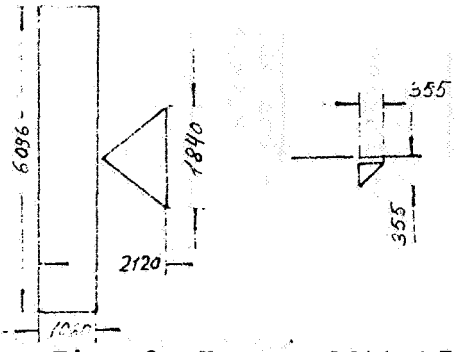

Fig. 2. Henson,1844-47

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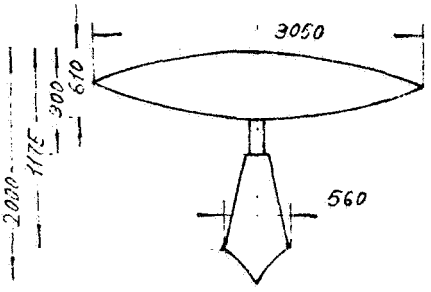

Fig. 3. Stringfellow,1848

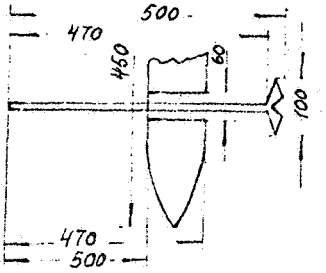

Fig. 4. Penot,1871

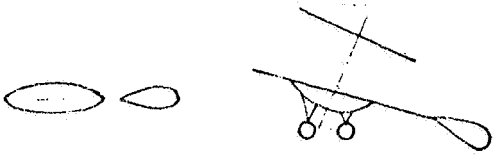

Fig. 5. Mozhayskiy,1876 (sketch)

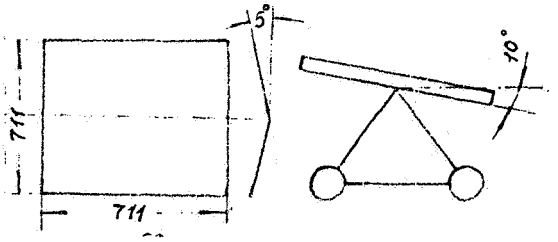

Fig. 6. Ewald,1868

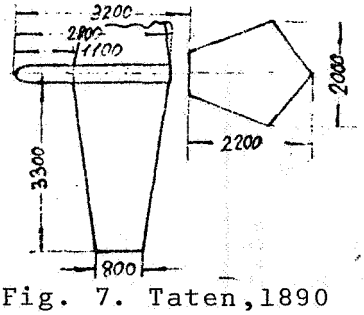

Fig. 7. Taten,1890

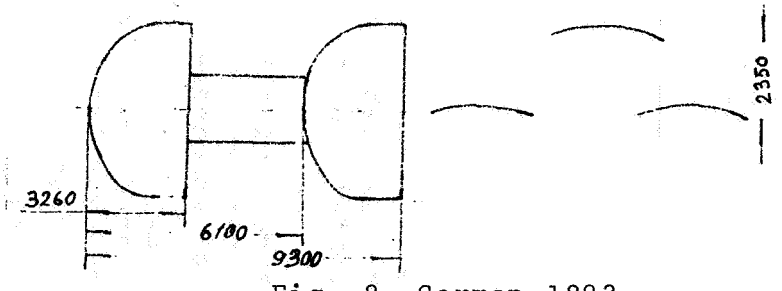

Fig. 8. German,1893

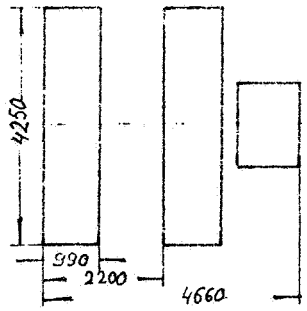

Fig. 9. Langley, 1896

From the condition of equilibrium of the pitching moments, we have the following: /41

$$\overline{X}_T = (m_{z_0,\text{-h.e.}}/C_y) + \overline{X}_{F,\text{-h.e.}} \quad (2)$$

Considering the fact that $m_{z0,\text{-h.e.}} < 0$, it follows from (2) that

$$\overline{X}_T > \overline{X}_{F,\text{-h.e.}} \quad (3)$$

i.e., the lack of horizontal empennage automatically requires attributing the quality of static "instability" to the model, the degree of which is determined quantitatively by the following value:

$$\overline{X}_T - \overline{X}_{F,\text{-h.e.}} = b\overline{X}_F = -(m_{z_0,\text{-h.e.}}/C_y), \quad (4)$$

while the value of $b\overline{X}_F$ cannot be constant, in relation to the change in the angle of attack, at least at various stages of the flight. The basic lack of a possibility of a balanced regulation of the model also determines the need of a horizontal empennage (at least) for the model.

I would like to mention that longitudinal stabilization is generally of particular importance in maintaining the general stability of the flight of the model. For example, if oscillations of the model relative to the longitudinal axis (all the way to angles of roll of $\pm 20°$) result only in the corresponding rotation of the vector of the lifting power and an insignificant decrease in its projection on the plane of symmetry of the apparatus, the longitudinal rotation in the same range of angles of attack can lead to a complete loss by the plane of its supporting properties, and ultimately to destabilization and cessation of steady flight.

Aerodynamic stabilization of a model by transverse and directional control was provided for by comparatively uncomplicated design methods. For example, we can compare the dimensions of the horizontal and vertical empennage in Henson's model of 1844-47 (see Fig. 2). They are missing completely in Penot's model and in Langley's earlier models. The longitudinal stability was the predominant function, but it takes up a narrow section of the entire spectrum of the control functions for a flying apparatus in the course of its physical modeling.

From the condition of equilibrium of the forces and moments acting on the model in stable flight, we can obtain the following functional relationship showing the necessity for the model to have horizontal empennage, as a function of its parameters:

$$\Delta C_Y \overline{L}_{h.e.} = (2G/S_S V^2) b\overline{X}_F = m_{z_0} \qquad (5)$$ /42

where ΔC is the coefficient of the lifting power of the empennage; $\overline{L}_{h.e.} = L_{h.e.}/V$ is the relative length of the h.e.; G is the weight of the apparatus, S is the surface of the wing; V is the airspeed of the model.

It follows from (5) that the necessity for a horizontal empennage can vary quantitatively as a function of the difference in $b\overline{X}_F$ for a given weight of the apparatus as well as the surface and shape of the wing in design and profile.

Since the coordinate of the focus was determined by the shape of the plane in the design, profile and airspeed range, variation in the degree of longitudinal static stability is possible only when the position of the center of mass of the model changes. It should be stipulated immediately that this possibility depends directly on the mass-inertial characteristics of the model and its bulk. Thus, with an increase in the mass and bulk, it is more limited. It is well known, for example, that this possibility was used widely by D. Keily in his model of 1804 (see Fig. 1). The apparatus, made in the shape of a pole with a light supporting plane and tail empennage, allowed for a wide variation of the position of the center of mass with the aid of an added load, so that the horizontal empennage was not so much a means of stabilization as an instrument for positive balancing; this, by the way, is a normal phenomenon for apparatus with a great deal of longitudinal static stability. For the types of models designed by Stringfellow, Mozhayskiy, and Langley (Figures 3, 5, and 9, respectively), which had substantial weight and bulk, the horizontal empennage acquired particular significance.

In order to compare the models according to the function of flight stability, some quantitative characteristic is necessary. It follows from (5) that the elements for comparison should be the surface of the horizontal empennage, its length, the value for the difference $\overline{X}_T - \overline{X}_F$, and the power coefficient of the longitudinal static stability (the weight of the apparatus or the unit load on the wing). The first two elements can be determined (for the majority of models) on the basis of the available historical information. The results of the calculations conducted are shown in Table 2.

Assuming that the coordinate X_F is proportional to the chord, and that X_T is approximately proportional to the chord, we can represent the unknown characteristic in the following way:

$$H = (S_{h.e.} L_{h.e.})/vG = (S_{h.e.} \overline{L}_{h.e.})/G \qquad (6)$$

where $S_{h.e.}$ is the surface of the horizontal empennage.

TABLE 2. CERTAIN CHARACTERISTICS OF MODELS OF FLYING APPARATUS OF THE 19TH CENTURY

Researcher	Year	C	S	E	V	X	$S_{h.e.}$	$L_{h.e.}$	$L_{h.e.}$	S_{v_0}	H	H_1
		kg	m^2	m	m		m^2	m		m^2	m^2/kg	m^{-1}
1.Keily	1804	0.097	0.099	0.345	0.578	1.2	0.014	0.95	1.65	0.014	0.246	65.5
2.Hensen	1844	12.6	6.41	6.096	1.06	5.77	0.929	1.236	1.06	0.062	0.078	1.34
3.Stringfellow	1848	4.07	1.2	3.05	0.635	7.75	0.357	1.20	1.89	---	0.166	3.44
4.Penot	1871	0.016	0.031	0.45	0.11	6.55	0.0015	0.18	1.64	---	0.15	120
5.Mozhayskiy	1876	?	$0.211v^2$	0.32V	V	0.5	$0.102V^2$	V	1.0	0.1	?	?
6.Ewald	1886	?	0.509	0.711	0.711	1.0	---	---	---	---	--	--
7.Taten	1890	33.0	8.0	6.6	1.70	5.42	3.09	2.5	1.47	---	0.137	0.81
8.German	1893	120	45.0	6.10	3.26	0.83	---	---	---	---	---	--
9.Langley	1896	13.6	8.4	4.25	0.99	2.15	1.68	2.5	1.26	1.68	1.56	1.50

Note: The question mark indicates a lack of corresponding characteristics or the impossibility of determining them on the basis of the available historical information; the ---signify a lack of corresponding characteristics in relation to the specific structural features of the model.

The values of H were calculated in Table 2. This value gives /44
an intrinsic representation of the reserve of longitudinal stability for the model. Naturally, unstable flight of the model could actually occur for a number of reasons. However, it is of interest that in the case of models with $H < 0.14$ (see Table 2), it is known reliably that they were unstable during flight; this gives us a basis on which we can establish the cause-effect relationship between the dimensions and distribution of the horizontal empennage and the results of the experiments.

In Equation (5), ΔC_y and $\bar{L}_{h.e.}$ were not separated. Thus, we are confronted with the question of which was "more important" in the effect of $\Delta C_y \bar{L}_{h.e.}$, the first or the second factor. It is clear that when $\bar{L}_{h.e.} \to 0$, the presence of a horizontal empennage leads only to an insignificant backward movement of the focus of the model, but this is not sufficient to guarantee longitudinal stability. Therefore, we are left with the problem of positive balancing. For example, if there were a central record of Henson's model of 1844 and of Stringfellow's model of 1848, which had a horizontal empennage of very short length, there would be no particular difficulty in showing the concrete methods which the researchers should have applied in order to guarantee flight stability of the models.

Table 2 gives data on the ratio $H_1 = L_{h.e.}/S_{h.e.}$ for several 19th century models. Our attention is quickly drawn to the small values of H_1 for the models of Henson, Stringfellow, Taten, and Langley. It is also seen that Henson's and Taten's models were not stable in flight ($H = 1.34$; 0.81), while Stringfellow's model of 1848 and Langley's model of 1896 were stable. This is understandable: in Stringfellow's case, we have $H = 0.166$, while $H_1 = 3.44$ is twice that for Henson's unstable model, and four times that for Taten's. As for Langley's "Aerodrome", its stability was maintained primarily because of the improvement of the longitudinal statics with the aid of a tandem wing. Finally, the completely improbable value of $H_1 = 120$ for Alphonse Penot's "Planefore" is almost twice the H_1 of Keily's model. It was not without reason that the expression "Penot's tail" (which is unjust when we consider Keily) found wide-spread usage after the flight demonstrations with "Planefore" in 1871.

Because we do not know the dimensions and weight of A.F. /45
Mozhayskiy's model, we cannot draw quantitative conclusions regarding its stability. It is true that a comparison could be made according to the characteristic $H_2 = (S_{h.e.}\bar{L}_{h.e.})/S$, which is close to H, on the condition that the sketch of the model shown in the collection of documents on Mozhayskiy [2] roughly corresponds to the actual model. This value, for Mozhayskiy's model, is equal to 0.475, which exceeds the similar characteristics for the models of Keily, Henson, Stringfellow, and Penot, and which indicates a reliable stability of the model (which was also confirmed by the result of his experiments). I would also like to add that the

model, as we can see from Figure 5, also had a high degree of aerostatic stability.

The effect of the degree of aerostatic stability on the longitudinal stability is particularly important for a model, in view of the predominance of automatic stabilization in the spectrum of its regulating function. Moreover, with an increase in the weight and bulk of a model, an increase in the degree of aerostatic stability remains, in fact, the only means of giving the model the admissible longitudinal characteristics.

It is impossible to give even comprehensive characteristics of the principal studies made in the field of aviation modeling during the 19th century in a short article. However, it can be said that the basic problem, that of guaranteeing a stable powered flight of the model, was successfully solved. The historical significance of physical modeling in the early stages of the development of aviation lies in this fact.

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FORMATION OF THE PRINCIPAL TYPES OF GAS-TURBINE ENGINES

Yu. S.Voronkov

ABSTRACT: The author presents the formation of the principal types of gas turbine engines (GTE's) in the form of a damped-oscillation process. It is shown that the beginning of this process preceded the appearance of the first models of GTE's. Innovations and new ideas were often the results of tests with the models, and not analyses of the principles on which the models were based. The end of the process came at the beginning of the 1950's, when all the main types of sonic GTE's had been successfully completed.

The formation of the types of aircraft gas-turbine engines /46
(GTE) is the principal problem in the history of their development, in which the most important focal points of the appearance and use of these engines are concentrated.

The term "type of GTE" is not static: it changes in relation to the technological development of the structure which it determines, becoming richer and more complex.

An interesting fact is that until the present, no single classification has been made of gas-turbine engines, although the principal types have been determined rather clearly. Thus, G.S. Skubachevskiy, for example, shows that "GTE's can be divided into two groups: turbojet engines (TJE) and turbopropeller engines (TPE). The bypass turbojet engines (BTJE) occupy an intermediate position". [1].

It must be said that the intermediate position of the BTJE's is not stable. Depending on various structures, this type of engine can best approximate either the TJE or the TPE.

This division was based on the difference in the means for producing the thrust. The division can be continued further, according to the structural characteristics of the elements in the gas-turbine engines.

M. Roy [2] also divides GTE's according to the method of producing the thrust, but he defines one more type of GTE, the turbofan (TFE), although there are no great differences between this type of engine and the bypass engine. Thus, we can say that the contemporary term "gas-turbine engine" includes three types of engine design which differ according to the means for generating the thrust: TJE, TPE and BTJE.

Using the classification proposed by Professor A.V. Kvasnikov, /47 we can consider the gas-turbine engine as a thermal air-propellant engine-actuator. The term "engine" here should be understood as the generator of motion, and the term "actuator" as a consumer-machine in relation to the engine [3].

In a gas-turbine engine, both the engine and the actuator are structurally connected, forming a single propulsion system which can be called the power system.

The working fluid used is very important in determining the power system.

Historically, the trend in the development of energetics has always been connected with the working fluid used. Water, which is a source of mechanical energy, was replaced by steam, which in turn was replaced by gas. This became possible because of the development of heat engineering and the increase in the level of temperature which could be attained.

At present, the working fluid (using the above-mentioned terms) of the engine is a gas, while the working fluid of the actuator is the air in the atmosphere.

An analysis of the structures of modern GTE's allows us to distinguish a group of elements common to all these types of engines: turbine, combustion chamber, compressor, and nozzle. This group of elements can be called (conditionally) an "elementary TJE".[1] From this point of view, TPE's and BTJE's can be considered as types derived from the TJE, despite the differences in the method of producing the thrust.

Using that assumption, we can say that the structural types of GTE's are those consisting of a combination of an "elementary TJE" and additional units designed for achieving qualitatively new results, i.e., elementary TJE + additional units = qualitatively new engine.

By the term "qualitatively new" engine, we mean an altered type of TJE which provides for carrying out tasks other than those for the original types. An analysis of the development of GTE's indicates the development of GTE's is accompanied by the production of new qualities intended for expanding the range of usage in aviation.

At the same time, it seems to us that this regularity is found not only in the development of GTE's, but in the development of

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[1]We will not be examining the propellant system of these engines here.

aircraft engines in general by technological means. Actually, we /48
can use the development of aircraft piston engines as an analogy. The piston engine without supercharger and with a fixed-pitch propeller accomplished certain tasks. As these tasks became more complicated, the engine was equipped with a supercharger, a turbocompressor, impulse turbines, a variable-pitch propeller, etc., until the series of new qualities was exhausted by the possibilities of the piston engine.

Of all the mentioned types of GTE's the simplest in structure is the TJE; obviously, it would be expected that this type would be the first constructed. In fact, the first aircraft models of gas-turbine engines were made according to the TJE type. The first flight tests with TJE's were conducted in Germany. W. Kamm, in his article "The State of Development of Air-Jet Engines in Germany" [4] (as of January 31, 1941) refers to the following developed (i.e., actually built) types of gas-turbine engines:

(1) Heinkel radial TJE (two types: one with minimum length and the other with minimum diameter).

(2) The TJE of the BMW plant in Munich: a semi-graduated central compressor was installed in the engine, and the blades of the turbine had internal air-cooling.

(3) The TJE of the BMW plant in Spandau (the design was similar to that of the preceding engine).

(4) The TJE of the Junkers plant, with an axial eight-stage compressor and non-cooled blades in the turbine.

(5) The TRDK (i.e., BTJE...Yu.V.) of the Daimler-Benz plant, a structural peculiarity of which was the use of an axial compressor with impellers rotating in the opposite direction (This was not tested...Yu.V.).

Somewhat later, flight tests with GTE's were begun in England. There, the first flying models were made according to the TJE type. This was the WI engine, built to F.Whittle's design. Flight tests with the engine were begun on May 14, 1941 [5]. However, if we turn to the designs and experimental developments preceding the appearance of the first flying models, we will discover that many of them were similar to the TPE, BTJE, and combined designs, which were much more complex in structure than the TJE. These were the plans of K.E. Tsiolkovskiy [6], the Swedish firm Ljungstrøm [7], /49
V.V. Uvarov's apparatus [8], Brown-Boveri [7], and many others.

In our opinion, this contradiction can be explained by the regularity found in the development of gas turbine engines. Before describing this regularity, we should note that the problem of designing mathematical apparatus for research in the history of technology has not been solved. Therefore, the proposed regularity is of a purely arbitrary nature, and is given as an initial hypothesis.

This regularity involves the fact that the development of GTE's follows a damped-oscillation curve, the limits of which are

found in two conditions: the condition of necessity and the condition of possibility. The point of intersection in space between these limitations means the production of the optimal model of engine for the given conditions.

By the condition of necessity, I mean all the tasks which require a certain type of engine (in the form of the original idea, the design, and the construction); by the condition of possibility, I mean all the situations which affect the realization of this type of engine (at the same stages of development).

The single purpose of the hypothesis proposed is to attempt to represent the development of GTE's in the form of a model of a certain oscillating process, the amplitude and period of which are governed by concrete historical laws. We can illustrate a confirmation of this hypothesis by the example of the formation of the principal types of GTE's and by the example of the formation of certain principal structural designs.

As a possible solution to the problem of the necessity of replacing the piston engine in aviation, it was proposed that the jet engine be used. This can be considered the beginning of the conditional oscillating process. At first, before the beginning of studies with experimental models, there was no great need for GTE's; therefore, the possibilities of their appearance were not definite. This circumstance was one of the reasons why a very large number of plans for jet engines with very different designs appeared. Each of them, in the opinion of its author, had certain advantages. As the need for GTE's became urgent, those least suitable for rapid realization were eliminated, and the most suitable were developed.

It was mentioned earlier that the simplest type, in terms of /50
structure, was the TJE. However, in the formation of ideas (and not designs!) the TJE type is derived from a type of engine with a prop-jet. A confirmation of this idea can be found in an article by M. Roy, written in 1930: "For very high velocities, the advantages of rockets (read"TJE's...Yu.V.) over the motor-propeller group are increasing, and it is not difficult to understand that eliminating the propeller and the corresponding group of turbine disks would result in a very attractive simplification of the design, and a significant decrease in the weight of the self-propelled system can be achieved". [9]

The wide-spread use of jet engines with propellers can be explained by the fact that the designers' minds were very strongly "fixed" on the regular motor-propeller combination; not knowing the limits of optimum usage of the propeller, the designers proposed using it much more widely than was warranted.

When the development of the idea of GTE's reached the stage when experimental models were produced, this necessity called for exploiting the available possibilities in the form of separate

combinations of piston engines.

At the end of the Thirties, piston aircraft engines (among other combinations) had superchargers and turbo-compressors. An analysis of this combination, from the point of view of theory as well as structure, shows that they had much in common with the principal subassemblies of GTE's: a compressor and turbine. The structure of these combinations had a determinant effect on the formation of the corresponding subassemblies of the GTE's.

Let us examine in more detail the formation of the structure of the compressor in the GTE's. As in the formation of the types of GTE's, there were various possible schemes for the formation of the structure of the compressor: centrifugal, axial, volumetric.

However, the necessity for a rapid construction of the compressor led to imitations of the compresors already used in experiments, i.e., centrifugal and (in part) axial compressors. Volumetric superchargers had been constructed for piston engines, but they were not used widely. At the same time, the predominant use of an axial, centrifugal or combined compressor at first depended on which type of supercharger was used most. Thus, in the cited article by Kamm, we read that "the question of using an axial or centrifugal compressor to a great degree was resolved in favor of the axial type, which naturally is related to the successful development of axial superchargers" (keep in mind that this is Germany...Yu.V.) [4].

The problem was solved in another way in England, for the following reason: "The aerodynamics of a centrifugal compressor used for supercharging a piston engine have been built up over an extended period of time by development and improvements in research laboratories, while studies on axial compressors were not given a comparable amount of attention until quite recently" [10].

One of the most serious problems in producing GTE's was the problem of combustion. The seriousness of this problem, in our opinion, can be explained by the fact that there were no such combustion chambers in the GTE's of the thermal engines existing at that time. Therefore, during the period when the first models of GTE's were being constructed and before optimal structures had been found, most of the possible solutions had been used. Thus, F.Whittle, after many experiments, decided on individual combustion chambers [5].

In V.V. Uvarov's studies of gas turbines [8], we see that in developing the first combustion chambers, particular attention was devoted to experimental investigations, since the state of the theory of combustion at that time did not provide a completely reliable and established method of analyzing and calculating the actual combustion process. These experiments resulted in the production of a progressive design for the combustion chamber: the annular type.

In producing other engines, different structures were used for the combustion chambers. These structures were based on the principal types mentioned above.

In analyzing the problems related to the construction of the turbines, a continuity starting with turbo-compressors is clearly seen, as was the case for the compressor.

From the point of view of reliable operation, the turbines should be efficient at high gas temperatures. In solving this problem for the GTE's, two methods were used: producing special heat-resistant materials and using special cooling systems.

Both variants, and a combination of them, began to be used /52
in designing turbo-compressors. In Germany, for example, about 24 special alloys for the turbine blades had been developed by different organizations by 1938 [11]; in England, in 1940, the Mond Nickel Co. produced a special alloyed steel, "Nimonick" 80, which was used very widely. However, this method, which was more promising, was also more time-consuming. Therefore, structures with cooled blades were given the most practical use (particularly in Germany). The use of cooled blades, even before World War II, permitted the design of turbo-compressors which operated on exhaust gases at a temperature equal to (or close to) 1000°C [12].

In examining the problem of the formation of the principal types of GTE's, we can see a rather clear tendency to produce combined apparatus, i.e., apparatus which combined in one structure certain units of a preceding type of engine (i.e., the piston engine) and certain elements of a following type (air-breathing jet engines).

In 1930, K.E. Tsiolkovskiy, proposing the design "Semi-Jet-Propelled Launching Scheme" [6], developed none other than a general scheme of a bypass combined prop-jet engine, in which the propeller and compressor were derived from the piston engine. Later, this tendency was reflected in studies by F. Whittle [18], Campini [14], and a number of others.

I would like to mention that this tendency was regular and warranted during the transitional period of aviation. Logically, it was warranted by the fact that the necessity for producing a new type of engine could be realized by the available possibilities in the combined design, in comparison with the "pure" designs for GTE's. This was also warranted by the structural (mainly the rapid production of the structure) and economical aspects (relatively low fuel consumption/unit).

The production and successful tests of a number of engines based on different variations of the combined designs also confirm this statement. For example, Campini's engine and the E-30-20 engine in the USSR (tested in 1947) are examples of this successful development.

The same tendency to produce combined apparatus is also seen in an examination of the formation of structural designs for BTJE's. The engine made by the firm "Metropolitan Vickers" - "Metro'Vic" F/3, the flight tests of which began in November, 1943, was designed around a type of BJTE with the fan placed at the rear /53 [16]. However, on examining the structure, we find that this is a variation of the design of the TJE F/2 made by the same firm; i.e., it can be said that in this case the BTJE F/3 is not a specially designed type, but a remodeling of a previous type.

In analyzing this type of GTE, particular significance was given to the economical aspect, since the use of these engines in a definite range of velocities allowed a considerable increase in the thrust because the throughput of gas per second at reduced temperature increased (in comparison with the TJE) while the fuel consumption remained constant.

This tendency to produce BTJE's on the basis of previous designs can be traced further. At the beginning and the middle of the fifties, the idea of a TJED (a TJE with division of the air to the compressor) was expanded. The TJED is a version of the BTJE in which the air pressure is identical in both passages. This engine design (the TJED) was examined theoretically [17], but no information was found regarding the use of such engines in aircraft.

At the end of the fifties, the formation of TJED's as an independent type of GTE was completed, and further development went along the lines of structural improvement.

From all the above, we can conclude that by the beginning of the forties the structural ideas of all the types of GTE's had been formulated.

In the classification of W.Kamm [4], the basis of which is a division of engines according to the method of producing an accelerated flow (single-flow and double-flow), the distribution is made according to the principle of the order of decrease in the specific fuel consumption or the increase in specific weight. The following types of engines are represented:

(I) - TJE
(II) - BTJE
(III)- TPE
(IV) - Motor-compressor JE.

All the types of subsonic GTE's are included in this classification. However, the formation of structures of GTE's (according to types) was made before the beginning of the fifties, when original designs (not combined ones) of TJE's, TPE's and BTJE's were beginning to be constructed.

It can be said that, by about 1953, the formation of the principal types of subsonic GTE's, (TJE, BTJE, TPE) was complete, and /54

the theory of these engines was formulated.

The problem of the interaction between science and technology during the period of the formation of GTE types is very important, but it requires a special examination. Therefore, we will limit ourselves to one comment in this article: the scientific disciplines which are directly related to the designing of GTE's did not always precede the production of the first experimental models, but were often the result of studies of them.

For a certain amount of time, the designs of GTE's were stabilized, i.e., there were no principal changes in the structure of the types. However, attempts have been made recently to change the existing designs radically within the limits of each type of engine.

Such a significant change in the structural diagram as that made by the English firm of Rolls-Royce in producing the RB-178 engine [18] does not change the type of engine, however. The three-shaft engine developed belongs to the BTJE type, as does the BTJE "Trent", which was produced by the same firm [19]. The principal structural characteristic of these engine designs is the actuating of the fan and two stages of the compressor separately from the corresponding turbines; each of the three shafts can rotate independently, with an optimum number of revolutions.

The above examination of the problem concerning the appearance of the principal types of GTE's indicates that the formation of these types can be represented in the form of a damped-oscillation process, the beginning of which preceded the appearance of the first models of GTE's. The end of this process comes at the beginning of the 1950's, when the formation of all types of subsonic GTE's had been completed.

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THE DEVELOPMENT AND USE OF LIQUID-PROPELLANT ROCKET ENGINES IN EXPERIMENTAL AIRCRAFT IN THE USA (1944-1953)

G.V. Skvortsov

ABSTRACT: By using liquid-propellant rocket engines (LPRE's) in high-altitude and high-speed experimental aircraft, the USA, at the cost of a great deal of effort and money, accelerated a solution to the problem of the "sound barrier" and the production of supersonic combat aircraft. Multiple experiments using LPRE's as the main engines on the experimental supersonic aircraft X-1, X-2 and D 558-II aided in the development of a reliable and powerful LPRE, the LR-99, which had a thrust of 22.6 tons and permitted studying hypersonic speeds at altitudes up to 150 km.

At the end of World War II, the increase in the speed of /57
fighters to transonic velocities showed the necessity for overcoming the "sound barrier", which had become a great hindrance in the further development of tactical combat aircraft. Use of the first air-breathing jet engines and rocket engines solved the problem of increasing the available thrust of the aircraft's power system, but the rules for aerodynamics at transonic and supersonic velocities were still not completely developed, so that the flight of subsonic aircraft in this range frequently led to emergencies and accidents.

For a complete solution to the problem of the "sound barrier", experimental investigations were necessary. The investigations conducted in the USA differed substantially from those in other countries.

With its vast industrial and technological resources, the USA (under the pressure of military groups aiming for supremacy in the air) adopted an accelerated method of parallel conduct of various types of research. In 1944, in addition to flight tests and wind-tunnel tests with model aircraft, the USA began a large-scale program of research in this range of speeds, with the aid of a number of experimental aircraft [1]. The execution of this program, which played an important part in the solution to the problem of the "sound barrier", required great expenditure (the design and construction of only three X-1 experimental aircraft cost 10 million dollars), and was not managed without a number of accidents and fatal results for the pilots [2]. However, this allowed the USA to carry out the first supersonic flight 6-7 years before similar flights were completed in England and France, despite the fact that the USA had lagged behind in air-breathing jet engines and rocket

engines, and it allowed the USA to obtain the necessary data for solving many problems in constructing supersonic combat aircraft designed for Mach 2 or 3.

England achieved this at a later date; with much smaller resources than the USA, the British stopped working on the aircraft after the first failures in investigating transonic velocities with the aid of experimental aircraft (the destruction of the experimental aircraft DH-108) until the results of investigations with flying model aircraft were obtained. In particular, England stopped a study in 1946 which had been going on for three years; it involved a supersonic experimental aircraft, the Miles M-52, with a turbojet engine with afterburner developed on the basis of the Power Jet W-2/700 engine [3]. /58

SELECTION OF THE POWER SYSTEM FOR U.S. EXPERIMENTAL AIRCRAFT

During the period from 1944 to 1958, the USA constructed more than 10 different experimental aircraft intended for investigating transonic and supersonic airspeeds. Most of these aircraft were supersonic (Bell X-1, X-1A, X-2; Douglas D 558-II, North American X-15, etc.) equipped with liquid-propellant rocket engines (LPRE). As a rule, turbojet engines (TJE) were used for the power system of aircraft for transonic speeds.

The selection of the LPRE for the first supersonic experimental aircraft (Bell X-1 and Douglas D 558-II), the development of which began in 1944-45, was governed by the fact that at that time the TJE's produced in the USA did not have a thrust higher than 1800 kg. (General Electric I-40 and TG-180), which would not have guaranteed the calculated speed (Mach 2) for these aircraft, even at low altitudes [4]. Increasing the thrust of the TJE's by using an afterburner still had not been mastered in the USA during these years. The use of LPRE's seemed more advantageous. In 1945, the firm of Reaction Motors began static tests with the new LPRE 1500 N 4C (6000-C4), which had a thrust of 2720 kg [5,6]. The use of this engine on the X-1 and D 558-II aircraft allowed a brief flight at the calculated supersonic speed, at a high altitude ($\sim$ 20 km) which produced a substantial decrease in the aerodynamic stresses on the aircraft and also increased the safety of the experiment.

The researchers also saw significant advantages in the autonomy of the LPRE's, in that they could concentrate on studying aerodynamic and physiological problems of supersonic high-altitude flight during the flights.

The practice of using LPRE's on the experimental aircraft X-1 and D 558-II experimental aircraft confirmed these advantages, despite the cases of accidents with the X-1 aircraft (because of troubles with the fuel system) and despite the fact that during the second half of this period (1952-1958), the ground thrust of the TJEAB's (turbojet engines with afterburners) already exceeded the /59

thrust of the aircraft with LPRE's (Fig. 1), subsequent experimental supersonic U.S. aircraft (Bell X-2, North American X-15) continued to be equipped with LPRE's.

SOME CHARACTERISTICS OF LPRE'S IN EXPERIMENTAL AIRCRAFT

An analysis of the requirements imposed on the LPRE's in the experimental high-speed aircraft, as well as the conditions and experiments involved in their operation in the USA from 1944 to 1958, provides the following characteristics for these engines:

(1) The LPRE's were launched and operated only under high-altitude conditions, i.e., the experimental aircraft began its flight from a mother aircraft at a significant altitude ($H \approx 9$ km).

Such launching eliminated the necessity for a rapid and dangerous take-off of the heavily loaded experimental aircraft with an operating LPRE from an airfield, and it conserved fuel for making a supersonic flight, which otherwise would have been consumed by the experimental aircraft during a climb to the altitude to which the mother aircraft had lifted it.

(2) The LPRE was used as the only engine on the experimental aircraft.

The decision not to use an additional TJE, which could have provided for greater distance and safety in the flight, was governed mainly by the idea of increasing the reserve of rocket fuel in order to achieve greater speeds and altitudes. The use of such a power system became possible and expedient only because of the particular conditions under which the experimental aircraft were operated: the launching of the experimental aircraft from the mother aircraft, the advantageous conditions for flight and landing, which simplified landing the aircraft with a non-operating engine (a special large airfield, the use of accompanying aircraft, etc).

(3) The low-boiling fuel components provided for greater specific thrust (oxygen, ammonia).

(4) It was necessary to control the thrust of the LPRE in the experimental aircraft very smoothly.

An experiment using the X-1 and D 558-II aircraft showed that a gradual regulation of the thrust of the LPRE 6000-C4, which was installed in these aircraft, caused sharp changes in stress, and often led to loss of the stability of the aircraft. During one of these flights with the X-1A aircraft, all four chambers of the LPRE stopped operating, because of a depletion of the fuel. This caused a complete loss of the maneuverability of the aircraft, and almost led to a serious accident.

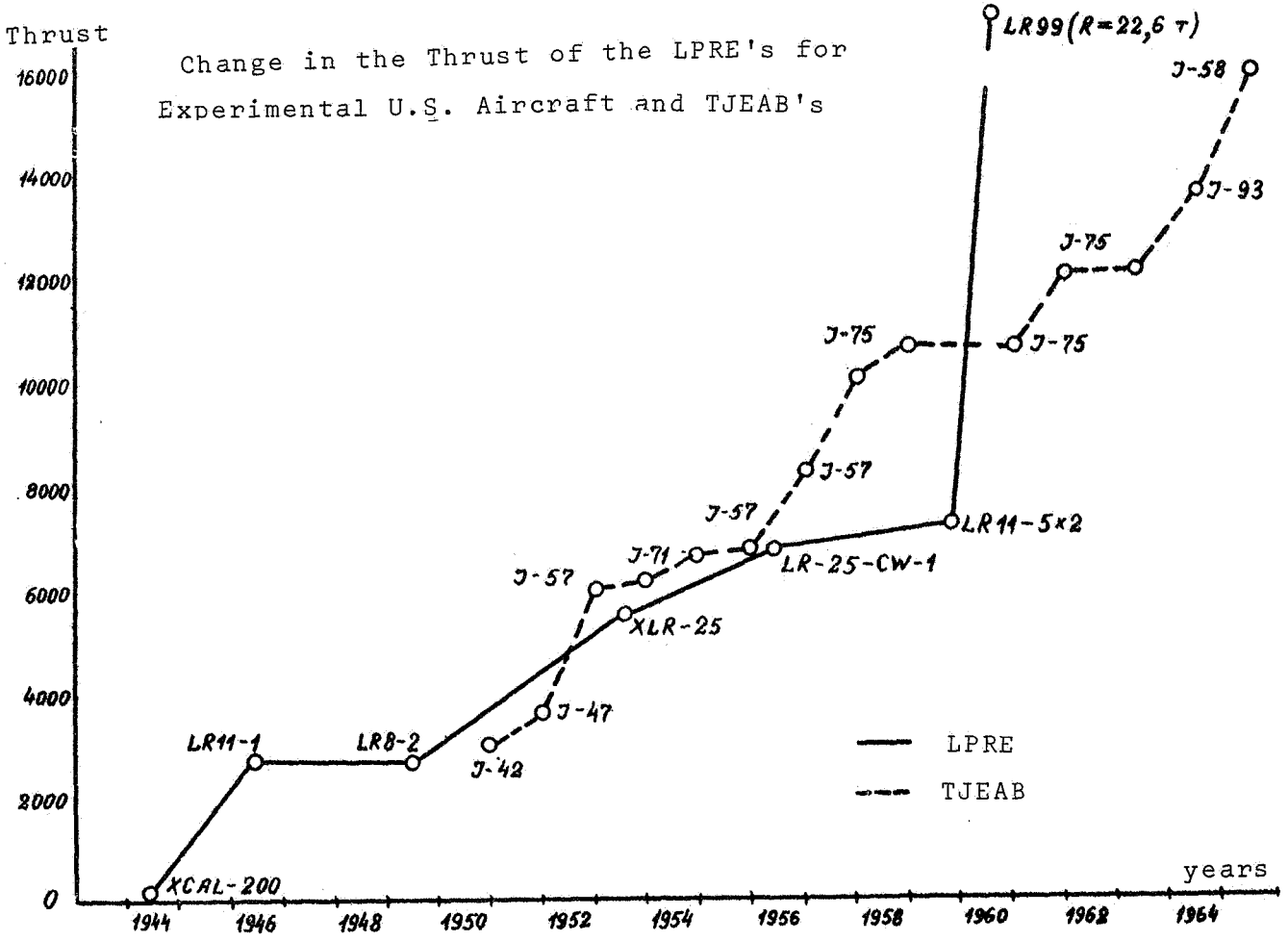

Fig. 1. Change in the Thrust of the LPRE's for Experimental U.S. Aircraft and TJEAB's.

THE PRINCIPAL STAGES IN THE DEVELOPMENT OF LPRE'S IN U.S. EXPERIMENTAL AIRCRAFT FROM 1944 to 1958 /61

On the basis of a division of the development of these LPRE's into periods, the focal moments in the designing of the power system for the experimental high-altitude and high-speed aircraft are located in relation to the particular characteristics for their use. On this basis, the development of LPRE's during this period can be divided into three stages.

1. The Production and Use of the First LPRE's on U.S. Experimental Aircraft (1944-1948)

During this period, the first U.S. aircraft LPRE's were designed, constructed, and installed in experimental aircraft: the XCAL-200 built by Aerojet, with a thrust of 90 kg, operating on nitric acid and aniline; and the XLR-II-1 made by Reaction Motors, with a thrust of 2720 kg, operating on a water-alcohol mixture and oxygen. Both of these engines were designed at a time when the U.S. engine manufacturers had only begun working on LPRE's, which were intended mainly for guided missiles and research rockets. In relation to this, the structure of the LPRE XCAL-200 and LR-II greatly reflected the idea of a "Universal" engine suitable for use on aircraft and missiles, i.e., the specific conditions of LPRE's operating on aircraft were not taken into account to a sufficient degree (the thrust of the LPRE XCAL-200 could not be regulated, while the thrust of the LPRE LR-II was regulated in stages).

Because the structure of the turbopump assembly (TPA) had not been perfected, both engines used an injection system for feeding the fuel; this lowered the payload and limited the fuel supply on the aircraft (the LR-11-1 on the X-1 aircraft burned for 2.5 min). The remaining engine parameters (specific thrust of 190 kg sec/kg, pressure in the combustion chamber of 20-16 kg/cm^2) also remained on the level previously attained by the German LPRE's.

Nevertheless, use of the LPRE LR-11-1 on the X-1 aircraft /62 allowed breaking the "sound barrier" in 1947 and making a number of supersonic flights at velocities up to Mach 1.5, at an altitude of 18.3 km (Fig. 2) [8].

The greatest altitude reached was 21.4 km.

2. Use of Engines with TPA's and Attempts to Design a Special LPRE for Experimental Aircraft (1949-1956)

At the beginning of this period, the Douglas D 558-II experimental aircraft was introduced with an LPRE LR-8-R-2 equipped with a TPA (a TPA was also used later on the LPRE LR-11). The use of TPA lowered the specific weight to a great degree and provided for an increase in the time during which the power plant could operate (3 min for the LR-8-2 on the "Skyrocket" aircraft, and 4.2 min for

the LR-11-5 on the X-1A aircraft). Thus, in 1951, a speed of M = 1.87 was reached with the "Skyrocket", while in 1958, M = 2.5 was reached with the X-1A aircraft at an altitude of 21.3 km [9].

However, the power system of the X-1 series of aircraft with a redesigned fuel system was very unreliable in operation, as a result of which there were explosions in the X-1-3 and X-1-D in 1951, and in the X-1-A in 1955 [10].

The necessity for studying high speeds and high altitudes required designing a power system with greater thrust. At the beginning of the fifties, Curtiss-Wright developed the LPRE LR-CW with a thrust of 5450 kg. This was intended particularly for the Bell X-2 experimental aircraft, designed for flights at M = 3 and H < 40 km [11]. This engine, like the LPRE LR-II, operated on a water-alcohol mixture and liquid oxygen, and was equipped with a turbopump system for feeding the fuel. However, in contrast to the LPRE's LR-11 and LR-8, it had a smooth regulation of the thrust and only two combustion chambers, one of which was intended specially for cruising.

Despite the lengthy adjustments of the LPRE LR-CW during the experiments, during which its thrust was increased to 6800 kg, the engine proved to be very unreliable; after accidents with two X-2 aircraft, studies with them were stopped. However, during the flights of the X-2 aircraft, a velocity of M = 3.2 and an altitude of 38.5 km were attained [12].

3. Development of LPRE's for Experimental Hypersonic Aircraft (1956-1958)

For a logical continuation of the research programs set up for the X-1 and X-2 supersonic experimental aircraft, by agreement of NASA, the US Air Force, and the US Navy, it was decided that the experimental aircraft X-15 would be designed for studying hypersonic flight velocities (M = 6-7) at altitudes up to 80 km [13]. According to calculations, in order to obtain such data the LPRE would have to have a ground thrust of about 23 tons. At the end of 1955, Reaction Motors was assigned this project. This engine, which was called XLR-99, was designed according to the results of experiments with the LPRE's LR-8 and LR-11 on the X-1 and D 558-II aircraft, and according to a strict observance of U.S. Air Force requirements that its operation be completely reliable. In comparison with these engines, the values for the specific thrust (250 instead of 192 kg sec/kg) and the specific weight of the LPRE LR-99 (0.018 kg/kg instead of 0.0575) were improved because of the use of a more effective fuel (anhydrous ammonia) and an increase of the pressure in the combustion chamber (42 kg/cm^2 instead of 16 kg/cm^2) [14]. In contrast to the other aircraft LPRE's built by Reaction Motors, the XLR-99 engine had one combusion chamber with regenerative cooling by the ammonia. The combustion chamber was made of steel tubes and was covered inside with a heat-insulating layer of zirconium

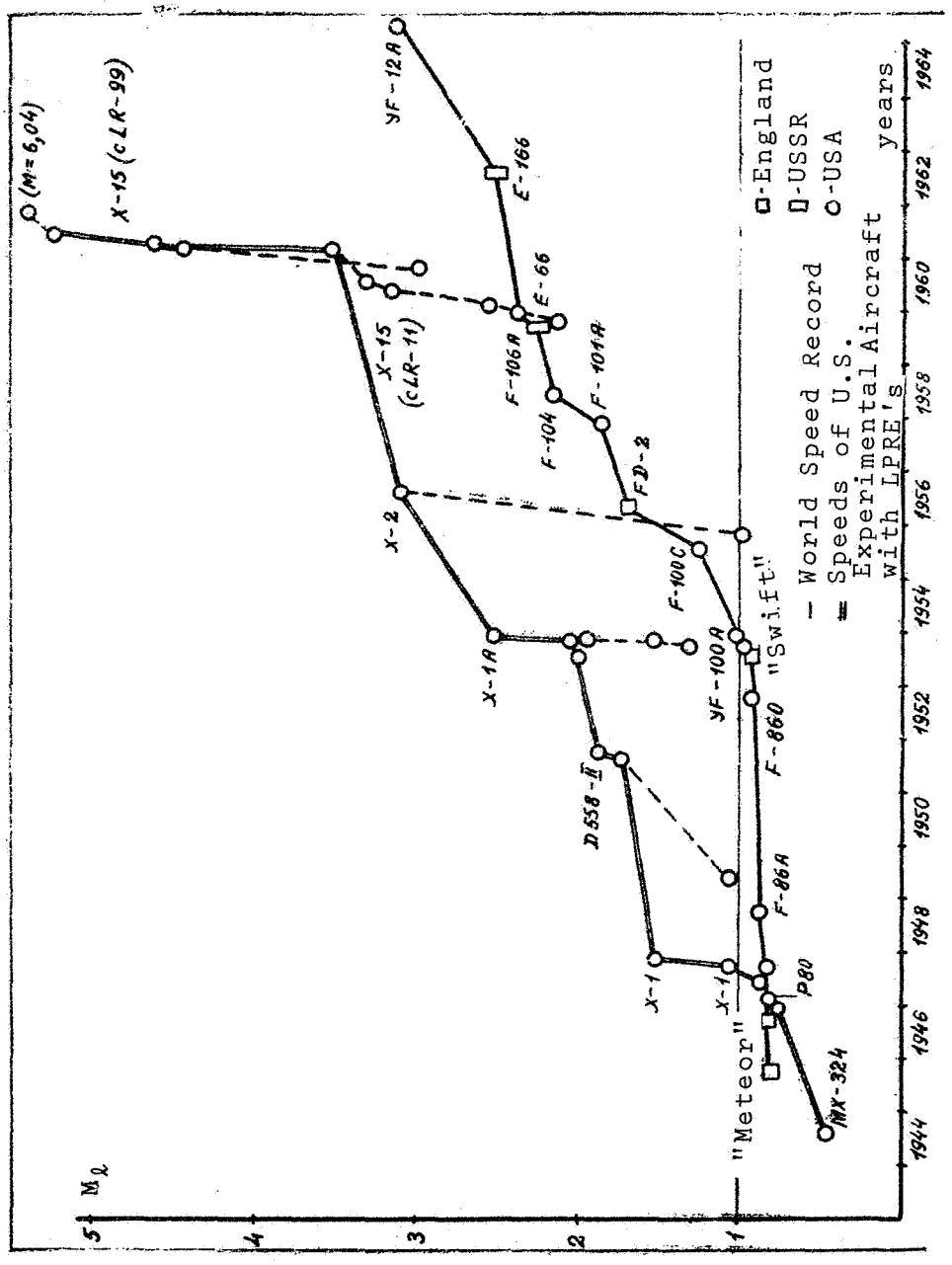
M
(M=6,04)
X-15 (cLR-99)
X-15 (cLR-11)
YF-12A
F-166
F-106A
E-66
F-104
F-101A
FD-2
X-2
F-100C
X-1A
YF-100A
"Swift"
D558-II
F-86D
X-1
X-1
F-86A
P80
"Meteor"
MX-324
England
USSR
USA
World Speed Record
Speeds of U.S. Experimental Aircraft with LPRE's
years
1944
1946
1948
1950
1952
1954
1956
1958
1960
1962
1964
1
2
3
4
5

Fig. 2.

oxide. The thrust of the engine was regulated by a throttle, within the range of 30-100% of its calculated value [15]. /64

In relation to the rigid requirements of the U.S. Air Force and the continuing maladjustments in the operation of the fuel system in the LPRE LR-11-5, particular attention was given to the reliable operation of the XLR-99 engine for each unit and to the fuel system in particular: in order to avoid accumulation of a critical quantity of fuel in the combustion chamber, a constantly-operating igniter was used. Most (up to 85%) of the operations in preparing the LPRE for launching were conducted on an experimental aircraft which was still suspended from the mother aircraft; the the draining of the fuel from the tanks was accelerated when necessary, etc. During the final adjustments, the LPRE-XLR-99 was subjected to multiple tests: length of operation, vibration, safety limits for possible failures, etc. Because of these precautions, the reliability of the engine was greatly increased, and it had a reserve of up to 60 minutes, instead of the thirty minutes for the LPRE LR-8-2 [16]. However, it took two years to put this engine into operation (the first flight of an X-15 with the LPRE LR-99 was completed only on November 15, 1961), and the cost of the studies increased, reaching about 50 million dollars by the middle of 1960 [17]. In relation to the delays in the final adjustments of the SLR-99, during the first two years (from November 15, 1959 to November 15, 1961) the X-15 aircraft completed flights with two LPRE's LR-11-5 developing a total thrust of 7260 kg (at H = 0), which allowed it to reach speeds up to M = 3.3 and altitudes up to 41.6 km. However, despite multiple redesignings of the fuel system in the LPRE LR-11, the flights of the X-15 with these engines often involved failures of the operation of the TPA or other units of the fuel system. /65

An analysis of the development of LPRE's in the USA for experimental aircraft during the period 1944-1958 shows the following:

(1) Due to the use of LPRE's on high-altitude and high-speed experimental aircraft, at the cost of a great deal of effort and money, the USA achieved an advanced development of this technological method (beginning in 1947) for studying the actual conditions of flight at speeds and altitudes which greatly exceeded those attained by the best experimental aircraft of that time. This allowed the USA to accelerate a solution to the problem of the "sound barrier" and the production of supersonic combat aircraft.

(2) The extensive experiments using LPRE's as the main engines on the X-1, X-2 and D 558-II supersonic experimental aircraft, with which 358 flights were accomplished with operating LPRE's, showed the substantial differences in the conditions under which LPRE's operate on experimental and combat aircraft, and demonstrated the necessity for developing special engines for them. These experiments also produced the necessary prerequisites for designing and building a more powerful and reliable LPRE (LR-99) which had a thrust of

22.5 tons, and which allowed studying hypersonic velocities at altitudes up to 150 km during subsequent years.

(3) The successful use of LPRE's on aircraft, at speeds and altitudes at which air-breathing jet engines provide the best characteristics, shows that in determining the range of expedient use for various types of technological methods, it is necessary to consider the condition of development of each type and the possibility of accelerating a solution to the scientific problems hindering the development of the given outgrowth of technology, in addition to a consideration of the general criteria.

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THE HISTORY OF THE DEVELOPMENT OF THE PRINCIPLES FOR DETERMINING THE POSITION OF AN AIRCRAFT IN SPACE, BASED ON THE USE OF A PENDULUM.

P. N. Polozhin

ABSTRACT: The principal developments in the types of pendulums used for determining the position of an aircraft in space are presented. The importance of the chronology of the patents granted in various countries for original structural designs of these pendulums is shown.

Various types of inclinometers were developed during the period from 1910 to 1924 to determine the position of an aircraft in space. For relatively low airspeeds (on the order of 100-200 km/hour) characteristic of the first series of mass-produced aircraft, the builders and designers applied their efforts to using the laws of physics, particularly to the use of ball bearings, liquids and pendulums in apparatus as the sensors, i.e., instruments based on the action of hydro- or aerodynamic pressure on the sensing system of the apparatus. /67

The electromechanical inclinometers of E. Müller and S. Spencer [1,2] are among the first navigational instruments with ball-bearing sensors. Spencer's instrument, for example, consisted of a casing containing leveling tubes or guide channels, along which the metal ball bearing moved. The guide channels were placed in the longitudinal or transverse plane at various angles. A shift of the ball bearing in each tube occurred when the angle of inclination of the aircraft became equal to, or somewhat greater than, the angle of inclination of the tube, so that the electric circuit to the indicator showing the inclination of the aircraft was closed.

In addition to ball-bearing sensors, liquids were also used in instruments from 1910 to 1915 to determine the angle of inclination of the aircraft. Thus, in 1910 V. Mackelpayne patented the simplest bubble level, consisting of a casing partly filled with liquid. The position of the air bubble on the spherical scale showed the divergence of the aircraft from the horizontal plane [3].

In 1911, C. Pallegren proposed a liquid inclinometer consisting of a glass spherical shell filled with two liquids which differed in specific weight [4]. The heavier liquid was dark in color, and the lighter one was light. The glass shell was fastened to a cardon joint equipped with a measuring scale and reference line. The magnitude of the divergence of the aircraft from horizontal flight was indicated by the line marking the division between the two liquids on the measuring scale. /68

In the electrical systems for indicating the position of the aircraft, A. Britering proposed using mercury as the conducting liquid [5]. The inclinometer was made in the form of two communicating vessels placed along the longitudinal and transverse axis of the aircraft and showing the inclination by closing a number of electrical contacts.

Pendulum inclinometers were made in many varieties, because of the apparent simplicity in using the properties of a pendulum to achieve a static position relative to the true vertical. Such designs for aircraft inclinometers were patented as early as 1910, by A. Wirt [6] and other designers.

In Russia, the engineer L. Kolpakov-Miroshnichenko announced the designing of a pendulum inclinometer in 1916, and obtained rights to it in 1917 [7]. The inclinometer which he proposed consisted of a casing partially filled with liquid, in which a pendulum was placed. The pendulum was suspended on a spherical bearing, and damped by a liquid. The upper end of the pendulum showed the position of the aircraft in relation to the longitudinal and transverse axes.

Instruments with pendulums or liquid sensors were also constructed during the following years. The inclinometers of I.A. Mikhaylov [8] and I.N. Chizh [9], with mechanical recording of the value of the inclination of the aircraft,can be included among such devices, as can the inclinometer of Ya. B. Borokhovich [10], with an electrical recording of the desired value. In Borokhovich's inclinometer, instead of a mechanical (pendulum) element, he used a pendulum which closed contacts in an electrical circuit at the extreme positions of the maximum permissible inclination of the aircraft (in relation to the longitudinal or transverse axes of symmetry).

An original design for an aircraft inclinometer was suggested /69
in 1917 by G. Vogt [11], and, independently, by A. Keynes [12]. It was proposed that a flame be used as the sensor. The flame would burn in a transparent spherical housing located in front of the pilot. The sphere would be firmly fastened to the aircraft. A gas-supply tube with a regulating device would be installed inside the sphere. In another version of this device, a disc was placed inside the transparent sphere over the flame. Heat-sensitive elements connected to the indicator by wires were placed along the periphery of this disc. With an inclination of the aircraft (and the transparent sphere), the flame would maintain its vertical position and heated a corresponding heat-sensitive element, which would then generate an e.m.f. to cause deflection of the indicating device.

In 1918, the firm Reichvervoltung [13] prepared a combined apparatus for simultaneous indication of the airspeed and the rotation of the aircraft relative to the direction of travel. The

apparatus consisted of two Venturi tubes mounted at the tips of the wings, and connected with the vanes of two pressure gages. Pointers were attached to the diaphragms of the pressure gages. When the aircraft turned, the difference in the aerodynamic pressure caused motion of the pointers, which showed the airspeed on the scale, as well as the angular velocity and the direction in which the aircraft veered. This idea was incorporated in many instrument designs. Similar indications of the inclination and the rate of turn of the aircraft relative to the longitudinal axis were also developed in England during the period from 1915 to 1920 [14,15].

Among the original indicators of the inclination of an aircraft were the devices described by A. Hefford in 1919 [16] and by G. Klanck in 1931 [17]. The operating principle of the instruments was based on use of the flow of free-flowing materials. The instrument consisted of a casing containing a sand-filled receptacle. The lower part of the receptacle had an opening through which the sand poured out onto an obliquely-positioned measuring scale. When the aircraft moved relative to the longitudinal or transverse axis, the point of contact of the poured-out sand was not at the zero index, but moved depending on the position of the aircraft relative to one of its axes. Compressed air was used to return the sand to the upper part of the casing. /70

Instruments of this type could not be used widely for a long time, because of a number of inherent disadvantages. The principal disadvantage of the pendulum inclinometer was the following: when external mechanical factors acted on the measuring system of the apparatus, its sensitive element diverged from the direction of the true vertical, making oscillating movements in relation to that factor for an extended period of time. Moreover, the comparatively great losses in the mechanical units of the measuring systems, caused by friction, lowered the sensitivity and accuracy of the measurements.

In addition to the operating principle which found structural realization in the apparatus, the patents also described principles which could be applied only in laboratories or under stationary conditions. The installation of such apparatus on aircraft was not feasible due to their sensitivity to acceleration and vibration.

For an analysis of the development of instruments with pendulums and other operating principles which we have examined, it is interesting to examine the table of patents granted in Germany, England, France and the USSR for the period from 1910 to 1940.

NUMBER OF PATENTS GRANTED FOR INCLINOMETERS FROM 1910 TO 1940

	1910-1913	1914-1918	1919-1924	1925-1930	1931-1935	1936-1940
Germany	7	24	12	18	9	2
England	20	64	40	15	7	3
France	1	--	3	--	1	1
USSR	--	1	1	7	6	--

The data in the table show that before World War I, the development of designs for pendulum instruments and apparatus of a similar type proceeded rather slowly: during World War I, a rapid development of these instruments took place. This is particularly clear from the number of patents granted in Germany and England.

Thus, we can see that there are three periods in the development of these instruments: a period of the origin of inclinometers, from 1910 to 1914; a period of the greatest development of inclinometers, from 1915 to 1924, and a period of decline in the development of these instruments, from 1925 to the end of the thirties. These three periods are characteristic of Germany and England. In /71
the USSR, the most intense period in the development of inclinometers come in 1925-1935.

The basis for studies of pendulum instruments and other operating principles lies in the patent literature, particularly the patent descriptions in Germany, England and Russia, and later in the Soviet Union. A characteristic feature the patent describes, in comparison with general technological literature, is the possibility of establishing a precise chronology for the origin of the idea and new technological solutions, since the publication dates of the new technological solutions in general technological literature, as a rule, do not coincide with the chronology for the origin of the technological ideas.

The fact that the publication dates in general technological literature do not coincide with the chronology of the events is due to a great many factors, including (for example) commercial considerations, competition between different firms, and primarily the nature of the laws in different countries, according to which the publishing of inventions excludes the possibility of future patents and gives the inventors the sole right to commercial use of the invention.

An analysis of several designs and models of the instruments and the operating principles examined shows the following:

(1) The origin and development of aerial navigation apparatus of pendulum type during the period from 1910 to 1940 occurred almost simultaneously in different countries of the world, while the various operating principles demonstrated by these instruments were, as a rule, the independent creations of scientists and designers in each country.

(2) Pendulum flight-navigation instruments were used during the period from 1910 to 1925 in view of the imperfections of other designs of that era.

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